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Green economy

Sustainable growth, green finance and economic transformation

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EcoNova brings together eleven interdisciplinary studies at the intersection of economy, ecology, innovation and sustainable development. The special issue addresses industrial air pollution, urban heat, ecosystem restoration, green finance, municipal governance, natural zeolite, agricultural land potential, agribusiness marketing, passive carbon capture, blue-green tourism, life-cycle assessment and green entrepreneurship, linking environmental evidence with practical pathways for resilient development.

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FOREWORD FROM THE EDITOR-IN-CHIEF

“ Making Peace with Nature

Dear readers,

EcoNova, the first special issue of JGEOR, appears at a moment when the relationship between economic development and the natural world is being reframed with unusual urgency. Sustainability is no longer a peripheral environmental concern. It increasingly shapes questions of investment, public policy, urban development, food and water security, technological innovation and the long-term resilience of economies and communities.

In its priorities for 2026, the United Nations has renewed a clear call for “peace with nature.” The Secretary-General has warned that climate chaos cannot be separated from peace and development because it intensifies pressures on land, water and food, displaces communities and weakens the ecosystems on which societies depend. This framing is especially important for economic research: ecological degradation is not an external issue, but a source of material risks, fiscal pressures and lost development opportunities.

The same message is reflected in the United Nations’ 2026 call on biological diversity. Biodiversity is described as the living web that sustains humanity, while climate disruption, pollution and the overuse of land, ocean and freshwater continue to push natural systems towards breakdown. The UN has urged faster implementation of the Kunming–Montreal Global Biodiversity Framework, stronger financing and capacity, and action that extends beyond governments to local communities, young people, academia, businesses, cities and regions.

“Making peace with nature requires evidence, restoration, responsible finance and decisions that recognize ecological limits.”

This perspective is closely aligned with the purpose of EcoNova. The issue connects economy, ecology and innovation through studies of industrial pollution, urban heat, ecosystem restoration and green finance, municipal governance, natural zeolite, agricultural land potential, agribusiness marketing, passive carbon capture, blue-green tourism, life-cycle assessment and green entrepreneurship. The topics differ, but they share a common principle: environmental conditions and economic choices must be assessed together if research is to support resilient and sustainable development.

For JGEOR, this means giving greater space to evidence that can move between disciplines and scales. Remote sensing, environmental indicators, economic assessment, governance analysis and resource evaluation can each support better decisions when they are methodologically transparent and interpreted with care. As Editor-in-Chief, I want EcoNova to demonstrate that interdisciplinary research is most valuable when scientific evidence is connected to practical responsibility. Our commitment remains constructive peer review, open access, transparent authorship, research integrity and an editorial culture that treats nature as a fundamental condition of development.



Ulvi Mammadov

Editor-in-Chief · Journal of Green Economy and Optimization Research

Context sources

United Nations. (2026). Secretary-General’s remarks to the General Assembly on priorities for 2026. un.org

United Nations. (2026). International Day for Biological Diversity: “Acting locally for global impact.” un.org

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Assessing the relationship between industrial air pollution, vegetation cover and surface temperature in Temirtau, Kazakhstan

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Keywords

Google Earth Engine, industrial air pollution, land surface temperature, NDVI, Sentinel-5P

ABSTRACT

Monitoring methods are needed in the industrial cities of Central Asia that will link atmospheric pollution to the health of urban vegetation and surface thermal environments. This paper examines the effect of industrial air pollution on the vegetation cover and the land surface temperature in a city of Temirtau (Kazakhstan) during summer from 2020 to 2025 through a reproducible Google Earth Engine workflow. Harmonized Sentinel-2 surface reflectance was utilized to calculate the Normalized Difference Vegetation Index (NDVI); Landsat 8 and Landsat 9 Collection 2 Level-2 products were used to estimate land surface temperature (LST); and Sentinel-5P OFFL products were utilized to characterize tropospheric NO₂ and SO₂ column densities. Summer means were computed for the analytical zone with radius of 15 km and compared to the annual summer means of Temirtau with Pearson correlation. Mean NDVI ranged from 0.2862 to 0.4691, while mean summer LST ranged from 36.45 °C to 46.64 °C. Tropospheric NO₂ varied between 2.78×10^{-5} and 4.04×10^{-5} mol m⁻², whereas SO₂ showed a pronounced 2022 maximum followed by a decline to 3.30×10^{-5} mol m⁻² in 2025. The most significant correlation was found between the inverse NDVI and LST ($r = -0.797$, $p = 0.057$). There was an inverse relationship between NO₂ and NDVI ($r = -0.680$, $p = 0.137$) and positive relationships between pollutants and temperature which were not statistically significant. Results show marked coupling to vegetation and suggest that a combination of satellite vegetation indices can be used to assist environmental screening in industrial cities, but that the time series of the short annual duration must be interpreted with caution, avoiding causal explanations with the coarse-resolution atmospheric retrievals.

INTRODUCTION

Industrialization is a key element of urbanization, along with urban employment and infrastructure development, but it also focussed environmental pressures in urban areas where energy-intensive production, transport and residential activity occurs. Of these, one of the most visible is air pollution, as gases and particles are emitted from combustion and industrial processes resulting in impacts on ecosystems, human health and on the functioning of urban landscapes. According to WHO (2021), common air pollutants are a significant risk to health globally and evidence of their harmful health impacts has increased even at levels previously thought to be safe. For highly industrialised cities, environmental assessment thus gains from an approach which considers atmospheric pollution in parallel with indicators of vegetation condition and surface heating.

Kazakhstan is a highly relevant context for this integrated assessment. It has large industrial complexes, such as metallurgical, mining and energy complexes and has several cities in its industrial structure, which has historically had high levels of atmospheric pollution. According to Assanov et al. (2021), in 2019, eight out of 14 cities assessed in Kazakhstan experienced high level of air pollution in the atmosphere, and industrial emission sources were pointed out. Previous health analysis also revealed significant pollution-related health impacts throughout Kazakhstan and highlighted industrial cities as having a greater per-capita impact (Kerimray et al., 2020).

This shows that national average estimates of environmental quality in Kazakhstan are insufficient to grasp the quality of urban environments; a spatially and temporally explicit analysis of the influence of industrial environmental conditions on the quality of urban environments is needed.

Temirtau is one of the most famous industrial cities in the Karaganda Region, closely connected with the integrated iron and steel works. The city and its industrial environment have been of long-standing interest with respect to emissions to the atmosphere from metallurgical operations. Starikova and Yaroshenko (2016) reported seasonal changes in the level of atmospheric pollutants in districts affected by the metallurgical enterprise and dust, nitrogen oxides and sulfur compounds were found to be one of the major pollutants. National data from even more recent years also shows that Temirtau is one of the cities where industrial emissions and ambient air quality are important issues for environmental management (Assanov et al., 2021). The industrial profile of Temirtau is ideal for comparing the remotely sensed atmospheric parameters with the vegetation cover and surface temperature.

The environmental significance of vegetation is not just visual and recreational. Shading, evapotranspiration, albedo and roughness differences are all ways in which vegetation alters the surface energy balance. Thus on many occasions, green surfaces can be colder in terms of land surface temperature than sparsely vegetated or

impervious surfaces. This negative relationship between amount of vegetation and LST has been widely exploited in the study of urban heat island (UHI) (Weng et al., 2004). This relationship can serve as an ecologically relevant metric for thermal control in rapidly changing or industrialized environments and may be used to pinpoint areas where land-cover characteristics may exacerbate surface heat in summer.

This can be achieved in practice using remote sensing. The Normalized Difference Vegetation Index (NDVI) is a normalized vegetation index derived from red and near-infrared reflectances (Tucker, 1979). Land surface temperature can be studied at the scale appropriate to the urban and peri-urban context, through thermal infrared data acquired by Landsat. The TROPospheric Monitoring Instrument (TROPOMI) on board Sentinel-5P provides data on various atmospheric constituents, such as N₂O and SO₂ (Veeffkind et al., 2012). These datasets can be multiplied over several years of environmental screening as long as they are processed in the same way in a cloud computing environment like Google Earth Engine, which enables reproducibility and a relatively low reliance on local computing resources (Gorelick et al., 2017).

This holistic view is substantiated by recent studies on the correlation between urban development, vegetation cover and land surface temperature. Qadimli and Mammadov (2026c), for instance, applied satellite data to evaluate urban sprawl and vegetation and surface temperature in Luanda, showing the utility of remote sensing in linking land-cover changes and thermal stress in a fast-growing city. Arifzade et al. (2026) assessed the economic and ecological linkages of PM_{2.5} and PM₁₀ concentrations with industrial and transport sources in Sumgayit and Almaty, providing a representative example of the role that urban pollution plays in the socio-economic and environmental context in Kazakhstan. The present study adds to this reasoning by considering the area of Temirtau and by integrating both vegetation and surface temperature data as well as satellite-derived gaseous pollution indicators in one analytical design.

Such evidence is also policy relevant, and not only in the context of environmental monitoring. Urban environment, resource efficiency, low carbon investment and ecosystem services are now increasingly viewed as integral aspects of sustainable development in the context of green economy strategies. The importance of environmental projects for sustainable economic development is emphasized by Qadimli and Mammadov (2025), and the link between green city policies and air-quality and health-expenditure outcomes is established by Qadimli and Mammadov (2026b). Green finance is also crucial to facilitate greener infrastructure, renewable energy and environmental modernization – Azerbaijan's research has highlighted the importance of public awareness of green finance and financial tools for energy transition (Mammadov, 2025; Sadiqov et al., 2026). While the studies cover varying scenarios of geography and sector, they offer a policy context for understanding the environmental evidence that satellites can deliver for industrial cities.

Though the significance of Temirtau, there is still a lack of compact multi-indicator studies that assess summer vegetation condition, thermal patterns and NO₂ and SO₂ dynamics observed by satellites over a common recent period. Ground monitoring is essential to regulatory assessment but satellite data can be used to complement this by offering consistently spatial coverage and by uncovering relationships between environmental elements. Meanwhile, satellite products have limitations: TROPOMI can give the information of the column in the atmosphere, but not the near-surface concentrations, and the spatial resolution is much lower than Sentinel-2 or Landsat. Therefore, a methodologically careful study

needs to be able to differentiate between exploratory association and causal attribution and must not compare two column densities directly with concentration-based health guidelines.

The aim of this work is to evaluate the correlation between the indicators of industrial air pollution, vegetation cover and the temperature of the ground surface in the summer period of 2020-2025 in the city of Temirtau. The three questions addressed by the analysis are: (1) what was the temporal evolution of the mean vegetation index of summer (NDVI), of the mean land surface temperature (LST), of the mean tropospheric concentrations of NO₂ and SO₂ over the 6 years? (2) what were the spatial patterns of vegetation index and land surface temperature in 2025? (3) what was the direction and strength of the annual relationships between vegetation, temperature and the concentration of atmospheric pollution indicators (NO₂ and SO₂)? Google earth engine is used to harmonize the datasets, to calculate annual means and to estimate Pearson correlation. The desired deliverables are a set of reproducible urban environmental screening framework that is informative for industrial ecology and green-city planning and is explicit about the limitations of short time series and satellite retrievals.

LITERATURE REVIEW

Industrial air pollution and context of Temirtau

Industrial pollutions are always called a key issue of urban air quality in the environmental literature of Kazakhstan. Assanov et al. (2021) analyzed the trends of industrial emissions and the level of air pollution in cities in the country and found that there were cases of non-correspondence between emission permitting trends of the large power and metallurgical companies and rapid emission reduction. The results of their analysis indicated that there were a few cities that continued to be in high-pollution categories and Temirtau was among the industrial cities that needed attention to suspended particles and gaseous pollutants. Important is this national evidence that demonstrates that the environmental situation of Temirtau is not simply an urban phenomenon and is closely tied to the more general fossil-energy and heavy-industry reliance.

Scientific research related to health supports the relevance of this problem. In 2020, air pollution was investigated by Kerimray et al. in Kazakhstan, and it was estimated that there was a significant mortality burden from PM_{2.5} exposure in 21 cities. Their findings found several cities such as Temirtau, with high industrial pollution, to have high per-capita impacts related to pollution. The value of environmental monitoring coupled with public-health interpretation was also illustrated. Although health impacts are not estimated in the present research, this literature gives an important justification for considering the spatial and temporal evolution of pollution indicators not just as an atmospheric-science question, but as a sustainability problem.

There has been long-term evidence of the association of the local atmospheric conditions with metallurgical activity in the Temirtau area. Starikova and Yaroshenko (2016) conducted analysis of the districts affected by the large steel company and found that in summer, as well as in other seasons, an increase in several pollutants was observed. They highlighted NO_x and sulfurous compounds as relevant contaminants and spatial variations between urban districts. The results are particularly relevant to satellite observations during the warm season (June-August), as they indicate that warm season is not environmentally neutral. However, measurements of concentrations from the ground and satellite measurements of columns are different measurements of the atmosphere. The latter may suggest variability in

time and loading in the atmosphere, but should not be used to replace data from the regulatory stations.

The recent complementary perspective is offered by Arifzade et al. (2026) who analyzed PM_{2.5} and PM₁₀ in Sumgayit and Almaty with regards to industrial and transport factors. How they engage in comparative economic-ecological approach is relevant for the present research in two ways. Second, it helps to establish the assumption that environmental exposure in cities is influenced by industrial and transport structures. Second, it shows the importance of going beyond just one pollutant to the idea of how environmental indicators relate to urban systems. Temirtau is not as Almaty, its industrial identity is more strongly associated with heavy metallurgy, but the general understanding of the analytical principle is valid: urban pollution cannot be read as a data series alone, but only in conjunction with land use, economic activity and environmental management.

Land surface temperature and remote sensing in relation to vegetation NDVI is one of the most popular vegetation indices used in environmental remote sensing. The concept of its application is based on the fact that healthy vegetation is highly reflective in the near infrared while chlorophyll is strongly absorbing in the red part of the spectrum. Tucker (1979) demonstrated the usefulness of the red and photographic infrared combinations to monitor vegetation and a normalized index, which was later widely employed in ecological and land-cover studies, was developed. In an urban-industrial environment, the NDVI is not directly a measure of biodiversity or ecosystem health, but rather a measure of the relative amount and strength of green vegetation in the spatial and temporal constraints of the imagery.

The correlation vegetation-land surface temperature is equally methodologically based. Weng et al. (2004) proved the close relationship between vegetation abundance and remotely sensed surface temperature and how this can be used to assist urban heat-island analysis. Built up, bare and industrial surfaces are more likely to store and re-radiate heat energy, whereas vegetated surfaces provide more shading and evapotranspiration. However, the relationship between NDVI and LST is context-dependent as soil moisture, surface materials, irrigation, topographic features, meteorological observations, and timing of satellite overpasses also impact LST observations.

This vegetation-thermal coupling is still being employed in recent studies to interpret urban environmental change. Qadimli and Mammadov (2026c) evaluated urban expansion, vegetation patterns and surface heat distribution in Luanda, demonstrating that multi-source satellite analysis can be used to discern spatial differences between greener areas and warmer built environment. Although the study is geographically far from Temirtau, it still shows the applicability of the use of an integrated framework of NDVI and LST in different urban climates. By combining these high-resolution surface indicators with the data from the atmosphere, such as vegetation or temperature, an additional dimension of industrial pollution is added that is not provided by vegetation and temperature alone.

This multi-sensor analysis can be especially well performed in the cloud-computing environment of Google Earth Engine. As reported by Gorelick et al. (2017), Earth Engine is a platform that collocates a large geospatial data catalog with scalable computation, enabling researchers to process long archives of satellite data without having to download each scene to their local machines. This is useful if it is needed to create annual seasonal composites from Sentinel-2, Landsat and Sentinel-5P data collections with consistent temporal filters. The

method is also more reproducible since the collection identifiers, band selections, masking rules, and aggregation periods can be recorded in an executable code.

Sentinel-5P/TROPOMI brings the remote sensing analysis from the land surface up to the composition of the atmosphere. According to Veeffkind et al. (2012) TROPOMI is an instrument to measure important constituents of the atmosphere with high sensitivity and better spatial resolution than previous global instruments. Earth Engine offers gridded Level-3 NO₂ and SO₂ products. The relevant NO₂ band is an estimate of tropospheric vertical column density (VCD), while the SO₂ band is an estimate of VCD, both in mol m⁻². They have a fundamentally different measurement geometry and spatial support as compared to the land-imaging data (10-30 m). As a result, pollutant maps may not be fine-grained at the city level, and for small urban studies, the most defensible assessment may be temporal or area-mean and not neighborhood-based.

Green economy and environmental investment, Urban policy

Environmental monitoring becomes more useful if it is linked to decisions on urban investments and sustainable developments. According to Qadimli and Mammadov (2025), green economy programs can be considered as instruments for achieving economic development and environmental protection. For an industrial city, this means that the environmental performance has to be taken into account in the context of industrial modernization, energy efficiency, urban greening and the cost of pollution. While in isolation, satellite indicators can't singlehandedly tell you which investment should take precedence, they can help you recognize environmental trends that are in need of closer attention by regulators and funds.

Green-city policy is especially important in the context of vegetation-thermal part of this study. Qadimli and Mammadov (2026b) link green city policies with air quality and health expenditures in Baku and Ganja, emphasizing the potential co-benefits of urban environmental improvement. In the case of Temirtau, vegetation cover is not to be taken for granted to reduce industrial pollution, but urban greening can have an impact on thermal regulation, ecosystems services and local environmental quality. The surface-system coupling indicated by the 2024 vegetation and temperature outcomes in the present study are therefore more likely to reflect evidence of a surface-system coupling than evidence of a specific policy intervention.

Financing is also a key aspect. Mammadov (2025) demonstrates that knowledge and perceptions of green finance influence the understanding of the younger population regarding environmental financial instruments and Sadiqov et al. (2026) take up the mechanisms by which green finance can facilitate the development of renewable energy. The general significance of the studies is transferable: the industrial environmental transition process needs technological options and financing structures supporting them and that has been studied for Azerbaijan. For Temirtau, investments in clean energy, emission control, energy efficiency and land restoration will probably be based on coordinated public and private investments, instead of independent environmental projects.

This also avoids a narrow focus on industrial emissions, as seen from the ecosystem perspective. Qadimli and Mammadov (2026a) connect ecosystem sustainability and green finance based ecotourism possibilities, exemplifying how environmental assets can be integrated into economic planning. Temirtau is not a case of ecotourism, but the conceptual lesson is relevant: the economic value of vegetation, water bodies, land quality and atmospheric conditions have an economic value. An integrated indicator framework can thus help to tell a

green-economy story in which industrial competitiveness is assessed more and more in parallel with environmental performance and liveability in cities.

The literature taken as a whole suggests that it is possible to make three propositions with regard to the present analysis. First, the industrial air-pollution context for Temirtau is well established, and the satellite-derived atmospheric indicators are contextually meaningful, although the source of the pollution is not identified. Second, there should be an inverse correlation between NDVI and LST, as vegetation reduces surface heating. Third, environmental monitoring should be seen as part of a larger process of transition, which also involves green-city policy, industrial modernization and environmental financing. Empirical testing of the first two propositions is conducted and the third is used as a policy lens for the discussion.

The challenge of atmosphere–surface coupling and the issue of spatial scale

The challenge of integrated urban environmental assessment is made complex by the different spatial and temporal scales of operation of atmospheric and land-surface processes. Within a single industrial parcel, even within a single residential district, vegetation and surface temperature can change significantly, while satellite retrievals of atmospheric temperature are for a much larger air column compared to the spatial resolution of the data and can include several land-cover units. This distinction should not be kept in mind as an invalidation of combined analysis, but as a shift in the nature of the inference that can be drawn. The fine resolution NDVI and LST data are more suitable for the spatial heterogeneity in the city while the Sentinel-5P data are more suitable for detection of the broad atmospheric patterns and the temporal changes across the urban-industrial zone. If all layers were treated as having the same effective resolution then false precision would be created.

The difference is particularly significant for NO₂. Tropospheric NO₂ is tightly coupled to combustion processes but the amount observed in a satellite column is also dependent on emission strength, chemical lifetime, sunlight, atmospheric mixing and transport. A high column thus does not necessarily point to a single source or an exposure concentration at breathing height, but reflects an increased atmospheric loading in an urban-industrial area. For multi-year comparison, the Earth Engine product employed in this study includes a tropospheric vertical-column variable and quality-screened observations (Google Earth Engine, n.d.-b). But for local source attribution, complementary wind fields and emission inventories and, ideally, ground observations would be required.

Sulfur dioxide is also an interpretive enigma. SO₂ can be produced by industrial combustion, metallurgical processes and sulfur containing fuels, though column retrievals can depend on the height of the plume and the atmospheric conditions. The Level-3 SO₂ product is provided in Earth Engine in mol m⁻² and is quality screened prior to aggregation (Google Earth Engine, n.d.-c). Therefore, the product can be used to answer a comparative question, rather than to be used as a neighborhood concentration surface, at the same time in an industrial city like Temirtau. This is why, the present work consciously focuses on the SO₂ time series, rather than offering a fine-grained urban pollution map using the coarse Level-3 pixels.

There are also interpretive boundaries for the land-surface indicators. NDVI is sensitive to vegetation greenness and is not directly an indicator of tree canopy, species diversity or ecosystem condition. A high value can be irrigated urban vegetation, cropland or productive grassland. LST is the radiometric surface temperature at the time of

the satellite observation and is not equal to air temperature at a weather station. However these measures are still useful as they provide a description of surface processes that affect thermal exposure and urban ecological functioning. NDVI and LST offer a physically interpretable surface system pair, which in conjunction with NO₂ and SO₂, offers atmospheric context.

This multi-scale logic aligns with the Earth-observation trends at a wider scale. Google Earth Engine has lowered the computational barriers to combining sensors with different spatial, spectral and temporal characteristics (Gorelick et al., 2017). Hence the methodological challenge has come to focus less on access to data and more on defensible harmonization and interpretation of data. The best way to use these different sensors for industrial urban research is not to extrapolate all the variables to a single, arbitrary spatial scale, but to retain the strengths of each sensor and compare indicators at the scale they are most valuable.

Environmental monitoring in Industrial transition

Monitoring is not an end; its worth is in its use in environmental governance. The challenge for the industrial cities is to ensure economic activity and decrease pollution, resource intensity and ecological pressure at the same time. In particular, the perspective on the green economy as outlined by Qadimli and Mammadov (2025) is pertinent because it views environmental efforts as integrated into the development process and not as an afterthought to the production decision. From a pragmatic perspective, pollution control, energy efficiency, land rehabilitation and urban greening are an integral part of the modernization of industry.

Environmental monitoring can contribute towards such modernization by providing repeatable indicators, independent of the projects to be invested, for Temirtau. A stable methodology allows a comparison of changes in vegetation, surface temperature and atmospheric columns if the same summer processing framework is updated year to year. While these satellite indicators would not supplant official monitoring, they could be used as an add-on tool to screen for unexpected changes, to assess the overall progress of environmental trends, or to convey environmental information to scientists and public.

Finance is also a focal point of a transition framework. The upgrading of process equipment, better recovery of heat, upgrading of emission control systems, electrification of auxiliary equipment, or securing electricity with less carbon is often a large capital investment that an industrial facility must make. When there are measurable environmental benefits, green financial instruments can minimise financing barriers. The importance of such instruments in renewable-energy development is shown by Sadiqov et al. (2026), and Mammadov (2025) points out that society's awareness of green finance is crucial for its acceptance and involvement. Although the projects can vary from those in Azerbaijan, these principles are applicable to industrial cities.

Urban ecological investment needs to be taken into account in addition to the industrial technology. Vegetation can help mitigate surface heat, help in stormwater management, enhance the visual environment and provide ecosystem services. Qadimli and Mammadov (2026b) highlight the relationship between green-city policies and air quality and health-related economic benefits, and Qadimli and Mammadov (2026a) demonstrate how ecosystem sustainability can be linked to financing and economic opportunities. The message for Temirtau is that parks or tree planting cannot fix industrial pollution, but that there is a source-control and a land-management aspect to environmental transition.

An effective monitoring system can thus help to facilitate a 'portfolio approach' to environmental policy. Industrial emission indicators can be monitored separately but also interpreted in one sustainability framework, which can also be applied to urban thermal conditions and vegetation cover. It is more informative than one composite index, as the variables of Temirtau's indices may have different trends. It also minimizes the potential of canceling out trends or fluctuations in one indicator (e.g. decrease in SO₂) by improvements in another one (e.g. increase in vegetation condition).

Industrial cities, environmental equity, exposure

The spatial equity is also an issue in industrial air pollution as environmental burden is not evenly distributed across a city. The environmental conditions in residential districts that are close to industrial facilities or transport facilities or prevailing downwind sectors may be different from those in green and remote residential districts. The temporal and spatial variations between districts impacted by the metallurgical complex (Temirtau) have been noted in the course of previous ground research (Starikova & Yaroshenko, 2016). The circular design adopted in the current study does not allow for the estimation of neighborhood exposure, but the findings reported in the aforementioned study reiterate the importance of not assuming that the city-wide mean represents the environment of every citizen.

Equity is also pertinent, in terms of urban heat. Shade and cooler environments, and vegetation, may vary greatly from neighborhood to neighborhood. These contrasts can be identified with high-resolution NDVI and LST but exposure analysis needs population information, housing characteristics and information on where people spend. Even though a low-NDVI industrial/open-land pixel can show strong contribution to the area-average LST, it does not necessarily reflect a residential exposure hotspot. On the other hand, a high density area with low thermal stress may be socially more significant than an unoccupied industrial site with a higher thermal stress. Future extensions of the framework of Temirtau should be based on this distinction between environmental intensity and the human exposure. The creation of such extensions is a strong incentive for health research in Kazakhstan. Kerimray et al. (2020) demonstrated the large health impact of air pollution in cities across the country, and the per-capita health effects at industrial sites can be particularly high. The present study does not perform exposure or disease outcome calculations but the mapping of vegetation and surface heat provides a means to link environmental conditions to future population-weighted mapping. These efforts may reveal if there is a correlation between districts with lower air quality and those with lower cooling ecosystem services.

Environmental equity is important for green investment too. Broad regional benefits may be created by industrial modernization, but investments in urban ecology may be targeted in already privileged places, thereby resulting in an inequitable distribution of benefits. Both aspects, the overall improvement of the environment and the spatial distribution of green infrastructure should therefore be taken into account in the green-city policy. However, Qadimli and Mammadov (2026b) highlight that urban environmental policies can have broader economic and health impacts. Shaping greening and rehabilitation in an industrial city to vulnerable areas can reinforce social aspects of the green transition.

This vision can be realized in the future Temirtau study by integrating the population, school, hospital and residential land-use data with satellite-derived LST/NDVI and measurements of the ground air-quality. This analysis would shift the focus from ecological

city-scale design to environmental planning that is sensitive to exposure. The present research is a step further in that evolution: it provides a replicable array of environmental indicators, and it reveals relationships that can help direct further investigation in a more socially nuanced way.

MATERIALS AND METHODS

Study area/analytical boundary

Temirtau is an industrial town in the Karaganda region, in the middle of Kazakhstan. Large-scale metallurgical production and its industrial infrastructure have significantly shaped its economy and spatial structure in the urban context. The city lies in a continental climate with significant difference between summer and winter temperature and a seasonal standardization is necessary for remote-sensing comparison. A point close to the urban center (50.05494° N, 72.96464° E) was used for the analysis and a circular analytical zone was created with a radius of 15 km. This boundary has been chosen to provide the main urban area, the surrounding industrial estate, the main water surfaces and the surrounding peri-urban vegetation, ensuring a consistent boundary for all the annual calculation.

The 15 km buffer is not an administrative boundary, but instead an analytical study area. This distinction is significant because the goal was to explore an urban-industrial environmental system, rather than to provide official statistical data for the city as a whole. To ensure spatial comparability of the indicators at the aggregate level, the same geometry was used for the Sentinel-2, Landsat and Sentinel-5P products. Where applicable, water, cloud, snow and invalid pixels were removed prior to calculating land-based means of NDVI and LST.

Research design and time window

Six consecutive summers (2020 to 2025) were used for a retrospective multi-sensor design. Images were chosen for each year between 1 June and 31 August (note: in Earth Engine, the end date is exclusive, so it was set at 1 September). There were three reasons for limiting the analysis to summer. First, it decreased the contamination from seasonal snow cover. Secondly, it enhanced the year-to-year comparison of vegetation phenology and surface temperature. Third, the previous research in Temirtau has revealed some significant changes in the atmospheric contamination level in the warm season period (Starikova & Yaroshenko, 2016), so summer is a period of interest for integrated environmental assessment (IEA).

All processing was done in Google Earth Engine, where the cloud architecture enables processing of multiple archives of satellite data using the same workflow (Gorelick et al., 2017). The methodological steps were: defining the analytical zone; preparing annual summer composites of the vegetation and thermal variables; preparing annual summer means of the atmospheric variables; calculating area-average annual indicators; visualizing annual summer spatial NDVI and LST patterns for 2025; and performing Pearson correlation between the annual indicators, all two-by-two. This design is thus not a source-apportionment or causal-inference study, but rather an ecological time-series screening study of six annual observations.

Sentinel-2 vegetation processing

The Normalized Difference Vegetation Index (NDVI) was used to characterize vegetation cover and was computed using the Harmonized Sentinel-2 MSI Level-2A Surface Reflectance collection (COPERNICUS/S2_SR_HARMONIZED). Because scenes processed with newer Sentinel-2 baselines are harmonized to be consistent with digital-number ranges from older scenes (Google Earth Engine, n.d.-a), the harmonized product can be used for

multi-year comparison. The spatial resolution of Sentinel-2's visible and near-infrared bands is sufficient for the study of urban vegetation, and the high revisit frequency (five days on average) helps improve the chances of getting good, clear images in summer.

Scenes were selected for the Temirtau analytical zone, the time period of June-August, and a scene-level CLOUDY_PIXEL_PERCENTAGE of less than 30%. The Scene Classification Layer was used in Pixel screening. Pixels labelled as vegetation (SCL class 4) and non-vegetated land (SCL class 5) were kept and water, clouds, cloud shadows and snow were removed from the vegetation composite. The surface-reflectance values were calculated by dividing the digital numbers by 10,000. The NDVI was computed for every valid observation using:

$$NDVI = (NIR - Red) / (NIR + Red) \quad (1)$$

where NIR is the Sentinel-2 band B8 and Red is the Sentinel-2 band B4. Normalized red and near-infrared reflectance is based on the well-known vegetation monitoring spectral basis (Tucker, 1979). A mean summer NDVI composite was created for each year and cropped to the common area of study. Valid land pixels were subsequently used to compute the annual mean NDVI at a nominal 30 m reduction scale. The 30 m reduction scale was used for computational consistency with the Landsat component, this does not mean that the original data in 10 m Sentinel-2 data was actually degraded in the visualization.

Landsat land surface temperature processing

The LST was computed using USGS Landsat 8 Collection 2 Tier 1 L2 data (LANDSAT/LC08/C02/T1_L2) and Landsat 9 Collection 2 Tier 1 L2 data (LANDSAT/LC09/C02/T1_L2). The products cover an atmospherically corrected surface-temperature band (ST_B10) with an output pixel size of 30 m. The multiplicative scale factor and the additive offset on the Earth Engine catalog are 0.00341802 and 149.0 K respectively for ST_B10 (Google Earth Engine n.d.-d). The observations from Landsat 8 were available for the entire study period, and the Landsat 9 observations were combined with the Landsat 8 observations in the years following the operational launch of Landsat 9 in order to increase the temporal sampling.

QA_PIXEL and QA_RADSAT information were utilized in quality filtering. The filled, dilated cloud, cirrus, cloud, cloud shadow and snow flags were eliminated, as were the water pixels for the land-surface analysis and the radiometrically saturated pixels were masked. To convert the scaled temperature from Kelvin to degrees Celsius, the following was used:

$$LST(^{\circ}C) = (ST_B10 \times 0.00341802 + 149.0) - 273.15 \quad (2)$$

All valid Landsat 8 and 9 surface-temperature observations were combined in each summer, then medianed to a single image for the summer. Median compositing reduces the influence of single extreme observations and contamination from residues and maintains the general summer thermal trends. At a reduction scale of 30 m, the annual mean LST was computed in the analytical zone.

Sentinel-5P atmospheric indicators

Sentinel-5P OFFL Level-3 NO₂ and SO₂ products were used to represent atmospheric pollution. The NO₂ collection (COPERNICUS/S5P/OFFL/L3_NO2) was reduced using the tropospheric_NO2_column_number_density band. This is a variable describing the density of vertical NO₂ columns in the troposphere in mol m⁻² (Google Earth Engine, n.d.-b). The SO₂ collection (COPERNICUS/S5P/OFFL/L3_SO2) was reduced using the SO2_column_number_density also in mol m⁻² (Google Earth Engine, n.d.-c). They are all products in the atmosphere and are

derived from TROPOMI observations, the mission design of which is aimed at global monitoring of atmospheric composition (Veeffkind et al., 2012).

The Sentinel-5P data in the analytical area and in the summer season were averaged to create the images of the mean atmosphere. The area-average values were then computed at a 1,113.2 m Earth Engine Level-3 grid spacing. It is important to note that these are values of the concentration of the chemical in an atmospheric column, and not at a ground station in micrograms per cubic meter. Thus, they are not directly comparable with WHO air-quality guideline values (World Health Organization, 2021) based on concentrations. Here, the atmospheric variables serve as annual indicators of the overall NO₂ and SO₂ loading over the Temirtau urban-industrial area, using relative values.

Analysis of the Sentinel-5P layers was performed and was not used as the primary cartographic output, although the visualization is available. The actual resolution of the satellite retrieval underlying the products is much coarser than Sentinel-2 or Landsat urban imagery, although the products are delivered as a 1.1 km resolution Level-3 grid. In this respect, direct side-by-side pollutant maps at the 15 km city scale can have a block-like appearance which may give a false impression of neighbourhood precision to the retrieval. The last figure is using temporal plots for NO₂ and SO₂, but preserving high-resolution maps for NDVI and LST.

Gathering and analyzing data from various sources

The annual data set included four variables for six years: mean NDVI, mean LST, mean column density tropospheric NO₂ and mean column density SO₂. Pearson's product-moment correlation coefficient was used to assess pairwise relationships. The main relationships of interest were NDVI-LST and NO₂-NDVI, NO₂-LST, SO₂-NDVI and SO₂-LST. Earth Engine's `pearsonsCorrelation` reducer was used to return both the correlation coefficient (*r*) and two-sided *p* value for each pair.

With a small sample size of *n* = 6, the inferential power is not high. Hence, magnitudes of correlation can be interpreted first of all as directions and strengths of the exploratory effect and statistical significance is reported transparently. A conventional alpha of .05 was used; values that approach this level are not considered significant. No effort was made to suggest that NO₂ or SO₂, themselves, caused a change in vegetation or temperature. Factors such as meteorology, land-use change, soil moisture, industrial operating conditions, urban development and others, not measured, may affect the annual means.

When comparing with description, percentage change was calculated as (Value2025 - Value2020) / Value2020 × 100. The results are summarized in two tables and in a four-panel figure. Annual environmental indicators are presented in Table 1. Correlation coefficients and *p* values are provided in Table 2. Figure 1 shows a spatial distribution of NDVI and LST in 2025 and a time trend of NO₂ and SO₂ in 2020-2025. The external contextual photograph of the Temirtau metallurgical landscape is an illustrative image and is not an analytical data set, thus it has been credited separately.

The quality assurance, comparability and reproductivity.

A number of quality-control decisions were made to make years comparable. The harmonised surface-reflectance collection is the one used for Sentinel-2 because changes in the range of the Digital Numbers in non-harmonised products may be introduced in the processing baselines after January 2022. The harmonized collection brings newer scenes in line with the earlier observations (Google Earth Engine, n.d.-a). Pixel-level Scene Classification Layer masking was used in conjunction with scene-level cloud threshold. This two-step

process minimizes the likelihood that cloud contamination will affect the annual median NDVI and also provide sufficient observations to create a stable summer composite.

Quality assessment for Landsat was done using the Collection 2 Level-2 QA bands instead of a scene-level threshold of cloud-percentage. This is critical as a scene that is clear overall may have local clouds or shadows in the area of study. Cloud, cirrus, shadow, snow, and water and saturation flags were not taken into account in the workflow used to reduce the thermal observations. The official ST_B10 scale and offset is used following the specification of the Level-2 surface-temperature product from the Earth Engine catalog (Google Earth Engine, n.d.-d). To ensure methodological consistency of the final composites, Landsat 8 and Landsat 9 were merged after applying the same processing function.

In this research, NDVI and LST were composited using median compositing method which is resistant to individual extreme value and residual scene artifacts. The gases NO₂ and SO₂ were composited using mean compositing since the intent was to describe average loadings of the atmosphere over all valid summer retrievals. These various reducers do not represent a statistical push to make the series equal to each other but are representative of the properties of the measurements. The temporal window and the geometry of the study area were kept constant in each annual result, which is more important for interannual comparability than using one single reducer for all variables.

The workflow was also inspected visually in Earth Engine map interface. Annual composites were checked for missing data and implausible edge effects and spatial discontinuities. The high resolution 2025 maps of NDVI and LST were kept for publication as their spatial structure is interpretable at the city scale. The maps of NO₂ and SO₂, on the other hand, showed the coarse pixel structure that was typical for the atmospheric products. But instead of smoothing those layers and making it look like artificial spatial detail, the publication design consists of area-mean time plots. The basis on which the tables and correlations are made, i.e. the value of the underlying atmosphere, is not changed.

Explicit processing rules and catalog collection identifiers are used to increase the reproducibility. The results of the study can be reproduced by the researcher using the same coordinates, buffer distance, date ranges, masks, band names, scale factors and reducers that have been used in Earth Engine. No proprietary environmental databases are relied upon for the analysis. However, actual numbers of reproductions may be affected by subsequent reprocessing of satellites or catalog changes. For this reason, the names of the collections, as well as the variables and the logic of processing are reported in detail, with the purpose of providing documentation of the version of the analyzed data.

Analytical assumptions and considerations of robustness

The main assumption is that the six annual observations of summer can be regarded as paired observations to explore for correlation. Pearson correlation is linear association and is influenced by influential years. In the current series, the years 2023 and 2024 are significant as they represent contrasting NDVI-LST scenarios. There are only six observations; if one year were omitted, the coefficient would be materially affected. Therefore, the analysis does not include outlier deletion. The years produced by the predefined processing rules were all kept, and the coefficients are considered to be descriptive evidence over the entire study period.

The second assumption relates to time aggregation. Summer compression means that within-season variability is minimized, but

they also help minimize the impact of short-term events and allow comparison of sensors that have varying revisit periods. Thus, it considers interannual environmental screening to be more important than episode analysis. For a few days, a pollution event can have ecological or health impact without a strong impact on the seasonal mean, and an unusually wet or dry summer can have an impact on the vegetation and LST over a longer duration. A monthly analysis in the future would be able to unravel these different temporal processes.

Boundary sensitivity is a third. The 15 km buffer is comprised of urban, industrial and peri-urban land. A built-up core would be more emphasized using a smaller radius and more agricultural and semi-natural land would be included in the count if a larger radius were used. The chosen distance was to catch the functional urban-industrial landscape evident in the maps. The mean NDVI and LST values are affected by the choice of boundary; however, the interannual direction of change is not likely to be influenced by the boundary choice due to using the same buffer in each year.

Lastly, the study differentiates between a statistical association and an environmental mechanism. The NO₂-NDVI relationship may be due to a direct or indirect pollution stress, or weather factors impacting both atmospheric dispersion and vegetation growth. Similarly, positive coefficients between pollution and LST can also be due to similar meteorological factors and not necessarily a direct thermal impact of the pollutants. Rather than using bivariate annual correlations to argue for a causal relationship, the next step is multivariate modelling, using precipitation, wind, humidity and industrial activity data.

Annual Data Matrix and Indicator framework.

The final analytical matrix consisted of one row for each summer year and four main columns: NDVI, LST, tropospheric NO₂ and SO₂. It was a deliberate simplicity. Six years is not enough for this to have been done with many derived variables, as this would suggest a degree of analytical sophistication that doesn't add any independent information. For each variable there is thus a direct correspondence with a measurement domain of the satellite: vegetation condition, land-surface thermal state, nitrogen-dioxide atmospheric loading and sulfur-dioxide atmospheric loading. This core matrix was used to calculate percentage changes and correlation coefficients, and not as independent observations.

Units were kept in their natural scientifically meaningful form. NDVI has no dimension, LST is in degrees Celsius, NO₂ and SO₂ are in mol m⁻². The numbers in Table 1 have been rounded for ease in reading, while the correlations were derived from the unrounded outputs from Earth Engine. This prevents any changes in the statistical results due to rounding. The figure shows trends from the underlying annual means as well. No normalization or composite environmental index was used because the variables used have different physical meanings, which would necessitate subjective weighting to combine and may mask the pollutant-specific behavior that is shown in the results.

The analysis was designed as a full case design. No imputation was necessary for all four indicators as they all provided valid annual values for all four years from 2020 to 2025. This is methodologically beneficial as the imputation in a series of this length could have a significant effect on the correlations. The complete annual matrix also allows the results to be independently recalculated with standard statistical software if desired. The Pearson coefficients reported here were mostly provided to maintain geospatial processing and basic statistical evaluation within the same reproducible environment as provided by Earth Engine.

RESULTS AND DISCUSSION

Annual dynamics of environmental indicators

Table 1 summarizes the summer mean values calculated for the Temirtau analytical zone. NDVI showed substantial interannual variability rather than a monotonic trend. The 2020 mean was 0.4084, after which vegetation greenness declined to 0.3090 in 2021, 0.2911 in 2022 and 0.2862 in 2023. The sequence then reversed sharply in 2024, when mean NDVI reached 0.4691, the highest value in the six-year series. In 2025 NDVI fell to 0.3490, remaining above the 2021-2023 values but below both 2020 and 2024. Measured from the first to the final year, NDVI decreased by 14.54%, but this endpoint comparison conceals the much larger within-period fluctuation.

Table 1. Annual summer environmental indicators in Temirtau during 2020–2025

Year	Mean NDVI	Mean LST (°C)	Mean NO ₂ (mol m ⁻²)	Mean SO ₂ (mol m ⁻²)
2020	0.4084	39.74	0.00002779	0.00012270
2021	0.3090	39.44	0.00003973	0.00009071
2022	0.2911	43.58	0.00003213	0.00018108
2023	0.2862	46.64	0.00004044	0.00008947
2024	0.4691	36.45	0.00003117	0.00007525
2025	0.3490	39.31	0.00003417	0.00003299

Land surface temperature displayed an approximately opposite sequence. Mean summer LST was 39.74 °C in 2020 and 39.44 °C in 2021, before increasing to 43.58 °C in 2022 and reaching 46.64 °C in 2023. The following year produced the lowest mean of the series, 36.45 °C, coinciding with the highest NDVI. LST then increased to 39.31 °C in 2025. The 2020-2025 endpoint change was only -1.08%, again illustrating why a simple start-end comparison would be misleading. The more informative pattern is the contrast between the low-greenness/high-temperature conditions of 2022-2023 and the high-greenness/low-temperature conditions of 2024.

The range of tropospheric NO₂ column density was rather small compared to the large variation in nadir view angle, but not monotonic. The lowest annual value of the summer mean was observed in 2020 at 2.78×10^{-5} mol m⁻². It increased to 3.97×10^{-5} mol m⁻² in 2021, fell to 3.21×10^{-5} mol m⁻² in 2022, reached the series maximum of 4.04×10^{-5} mol m⁻² in 2023, declined to 3.12×10^{-5} mol m⁻² in 2024 and increased moderately to 3.42×10^{-5} mol m⁻² in 2025. The endpoint increase from 2020 to 2025 was 22.95%. The data are indicative of tropospheric column loading; thus, the trend is indicative of a relative atmospheric signal over the study area and not a change in near-surface regulatory concentration.

SO₂ behaved differently. The 2020 mean was 1.23×10^{-4} mol m⁻² and declined to 9.07×10^{-5} mol m⁻² in 2021. A distinct peak of 1.81×10^{-4} mol m⁻² appeared in 2022. Thereafter, the indicator declined to 8.95×10^{-5} mol m⁻² in 2023, 7.52×10^{-5} mol m⁻² in 2024 and 3.30×10^{-5} mol m⁻² in 2025. The "change 2020-2025" was highest with respect to the endpoint with -73.12% for the four indicators. That the 2022 anomaly combined with the three year decline is large is significant, but the current design cannot identify what this anomaly is due to: industrial activity, meteorology, retrieval conditions or fuel characteristics, or emission control or a combination of these.

This means there is no indication of a common trend across the environmental variables in the annual series. In contrast, vegetation and LST exhibit a significant year-to-year negative trend, NO₂ has a peak in 2021 and 2023, and SO₂ has a prominent peak in 2022 and a fall afterwards. This heterogeneity reflects the complexity of industrial

urban environments, where the composition of the atmosphere, the surface and vegetation varies to a range of drivers and time scales. It also helps to justify the methodological choice of using several indicators and not a single proxy for environmental quality.

Spatial patterns in vegetation and thermal patterns and trends in the atmosphere

Figure 1 shows the spatial distribution of NDVI across the Temirtau study area during summer 2025. The map depicts a mosaic of vegetated and sparsely vegetated surfaces within the circular analytical area. More highly valued NDVI values are found around some areas of water and those that are peri-urban; lower values are found throughout the more extensive open, built and industrially modified areas. Note that the map should not be used as a land-cover classification as NDVI values may change as the crop phenology, grassland condition, soil exposure and soil moisture change. However, it shows that there are disparities in the distribution of vegetation around Temirtau, and there are sharp contrasts in green cover in an urban-industrial landscape.

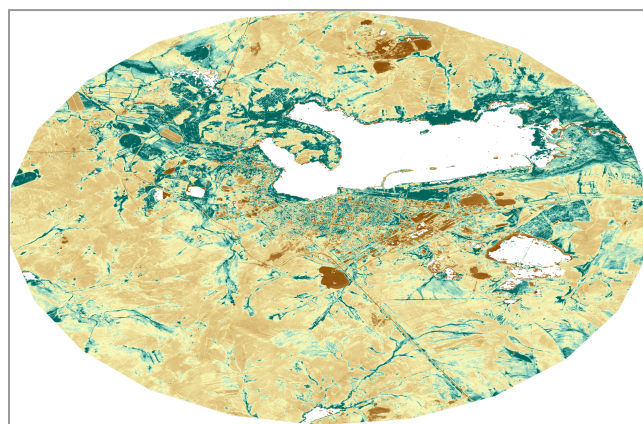


Figure 1. Spatial distribution of NDVI in Temirtau in summer 2025

Figure 2 shows the spatial distribution of land surface temperature in Temirtau during summer 2025. The thermal pattern differs substantially from the spatial distribution of vegetation shown in Figure 1. Warmup surfaces can be seen throughout open and built up areas while the water bodies and a number of greener areas seem cooler. The physically consistent of this pattern with the relationship between surface cover and urban thermal behavior given by Weng et al. (2004). This visual relationship between cooler locations and greater vegetation or water influence in the image supports the negative relationship between NDVI and LST in the annual statistics. The maps are spatial maps for one summer composite, however, and are not able to differentiate alone between persistent urban warming and short-term meteorological or surface-moisture influences.

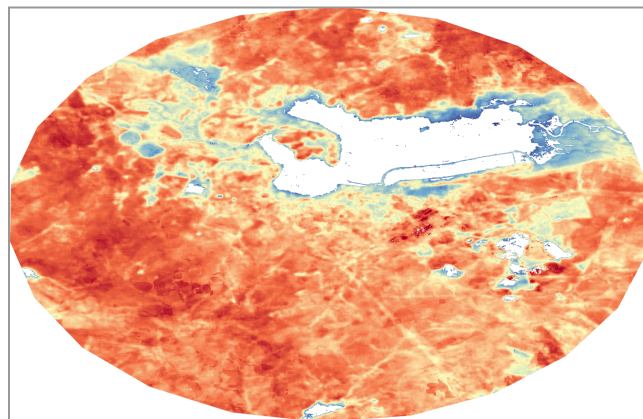


Figure 2. Spatial distribution of LST in Temirtau in summer 2025

Figure 3 shows that mean summer tropospheric NO₂ column density did not follow a consistent increasing or decreasing trend during 2020–2025. Rather, higher values were found in 2021 and 2023, lower values in 2020, 2022 and 2024 and a moderate recovery in 2025. This variation can be explained in an industrial urban system since satellite observations of NO₂ can be influenced by local combustion activities, but also by atmospheric transport, boundary-layer processes, cloud coverage and regional background concentrations. The outcome is thus most valuable as a comparative indicator on an annual basis. An interpretation at neighborhood level would be beyond the information content of the product.

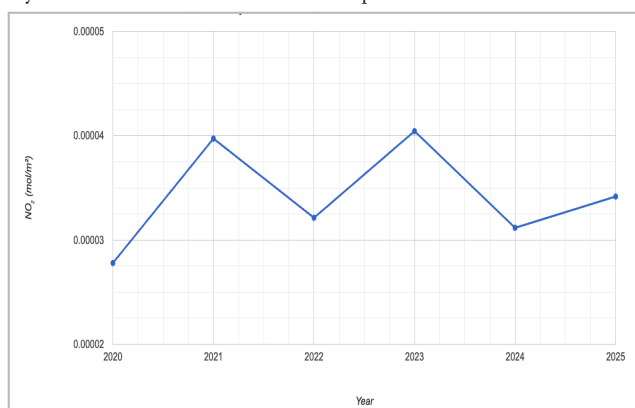


Figure 3. Mean summer tropospheric NO₂ column density in Temirtau during 2020–2025

Figure 4 shows a clearer medium-term directional pattern in mean summer SO₂ column density following the peak observed in 2022. Annual means are similar and decreasing from 2022. Sulfur compounds are historically related to metallurgical emissions from Temirtau (Starikova & Yaroshenko, 2016) and industrial emissions are one of the sources of urban air pollution in Kazakhstan (Assanov et al., 2021). However, the satellite series is not exclusive to the metallurgical complex; it is also not designed to account for wind and mixing in the atmosphere. The observed decline can thus be seen as a pattern of atmospheric change and not as any particular emission-reduction measure.

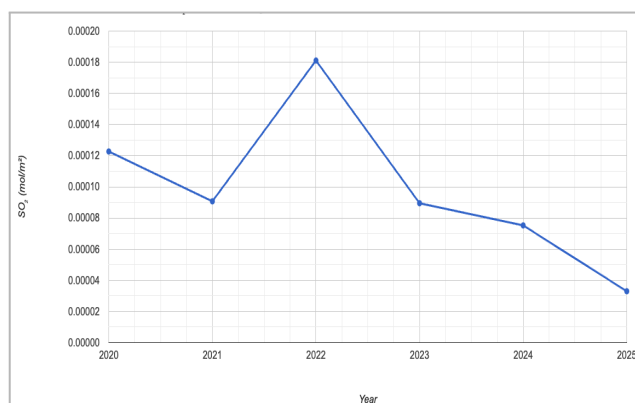


Figure 4. Mean summer SO₂ column density in Temirtau during 2020–2025

The contextual industrial image in this analytical result shows the physical dimensions of the metallurgical landscape that is spurring the study. It was for orientation only and not used for measurement, classification or validation. This distinction between analytical imagery and contextual photography is essential in remote-sensing research: while the visual impact of these industrial scenes might hint at the amount of emissions, only the stated satellite data and statistical methods have been used to reach quantitative conclusions in this paper.



Image 1. Industrial context of the Temirtau metallurgical complex. Source: Ilya Varlamov (2019), Wikimedia Commons, CC BY-SA 4.0.

Correlation structure among vegetation, temperature and pollution

Table 2 reports the Pearson correlations across the six annual summer observations. The strongest association was between NDVI and LST, with $r = -0.7974$ and $p = .0574$. The coefficient indicates a strong inverse relationship: years with higher mean vegetation greenness tended to have lower mean land surface temperature. The p value is close to, but remains above, the conventional .05 threshold. Accordingly, the relationship is described as strong and suggestive rather than statistically significant. The result is nevertheless internally coherent with the annual sequence, particularly the contrast between 2023, when NDVI was lowest and LST highest, and 2024, when NDVI was highest and LST lowest.

Table 2. Pearson correlations among annual summer environmental indicators ($n = 6$)

Relationship	Pearson r	p value
NDVI – LST	–0.7974	0.0574
NO ₂ – NDVI	–0.6797	0.1374
NO ₂ – LST	0.4776	0.3380
SO ₂ – NDVI	–0.2888	0.5788
SO ₂ – LST	0.3987	0.4336

This result is similar to the other remote-sensing works related to vegetation and urban thermal regulation. Weng et al. (2004) have proved that vegetation abundance and LST are close correlated in the urban heat-island studies and the Luanda assessment by Qadimli and Mammadov (2026c) has also shown the utility of analyzing the surface heat and the vegetation simultaneously in rapidly transformed cities. For the city of Temirtau, the value of the coefficient is negative and large, implying that the variability in green-cover is an important part of the variability in surface-temperature during summer. It is not a rejection of the idea that vegetation can influence thermal conditions; weather and soil moisture, surface materials and urban form were not used in the 6-year correlation.

NO₂ and NDVI were also negatively related ($r = -0.6797$, $p = .1374$). There is a moderate to strong inverse association with magnitude of statistical uncertainty. Several mechanisms could be reasonably suggested as credible mechanisms for creating such a pattern. Note that more vegetated years might also be coupled with wetter or meteorologically different summers that also affect NO₂ chemistry and dispersion, and more intense combustion and industrial activity might be linked to conditions that are bad for vegetation. These pathways cannot be distinguished in the present data. The coefficient should therefore not be considered to represent a direct effect of NO₂, as observed by satellite, on vegetation cover. The result should instead

be viewed as a suggestion or hypothesis for future analysis with monthly meteorological and emission data.

There was a positive relationship between NO₂ and LST ($r = 0.4776$, $p = .3380$), suggesting that a higher NO₂ was associated with a warmer summer, but the association was weak and not statistically significant. SO₂-LST was likewise positive ($r = 0.3987$, $p = .4336$), while SO₂-NDVI was weakly negative ($r = -0.2888$, $p = .5788$). These coefficients are qualitatively consistent with a theoretical model that suggests that increased thermal stress may accompany increased pollution and decreased vegetation, but the number of samples is too small to make a general causal statement. With only six observations per year, there are only four degrees of freedom for each correlation, and thus even fairly high correlation coefficients might not be significant at the conventional level.

The statistical results also show an important difference between the scientific relevance and the statistical significance of the results. In an exploratory short series, a coefficient like -0.797 may have an environmental significance as a descriptive pattern even though p marginally exceeds $.05$. The exact coefficient and p value is reported to give readers the sense of magnitude and uncertainty. This is better than simply dividing the evidence into categories of significance and non-significance without taking sample size, scale of measurement and physical plausibility into account.

Year-specific environmental interpretation

The combined effect of the indicators, from 2020 to 2025, is more informative than the individual indicators. The study area had relatively high NDVI (0.4084) accompanied by moderate LST (39.74 °C) and lowest NO₂ value in series 2020. This year serves as a good benchmark year as there was nothing extreme in terms of vegetation or thermal indicator. The next year indicated a significant reduction in NDVI (0.3090) with a minimum change in LST value. Meanwhile, NO₂ saw a significant rise and SO₂ fell. The mixed behaviour suggests that an increase in both atmospheric pollutants is not a simple explanation for the vegetation change.

In 2022, mean NDVI declined further to 0.2911 and LST increased to 43.58 °C. This combination is indicative of decreased vegetation greenness and increased surface heating. The most characteristic feature of the atmosphere in 2022 was the SO₂ maximum of 1.81×10^{-4} mol m⁻², which is more than double the 2024 value, and more than five times the 2025 value. However, the concentration of NO₂ was less than in 2021. The fact that the two atmospheric indicators do not follow the same evolution again indicates that the evolution of the pollution environment is directed by source-specific and meteorological processes, and not by a common evolution.

The year 2023 had the best high temp low vegetation year. The minimum of the series for NDVI was 0.2862 and the maximum for LST was 46.64 °C. NO₂ also peaked at a 6-year high while SO₂ approached its 2021 level. This combination is mainly responsible for the negative NO₂-NDVI and positive NO₂-LST coefficients. However, one year is not enough to set up a mechanism. A hotter and possibly drier summer could simultaneously cause lower vegetation vigor, increases in LST and changes in atmospheric chemistry or behavior of boundary layer. Thus, meteorological information is crucial for understanding the 2023 anomaly in subsequent studies.

The turnaround in 2024 is also significant. The NDVI rose to 0.4691, which is about 64% higher than in 2023, whereas the mean LST decreased by over 10 °C to 36.45 °C. Much of the strong inverse relationship between NDVI and LST is caused by this sharp transition. Additionally, NO₂ levels also fell from their peak in 2023, while SO₂ levels have been following a post-2022 downward trend.

The combined improvement in greenness, thermal conditions and both atmospheric indicators is environmentally desirable, however, and without supporting evidence, it is impossible to attribute the improvement to any single policy or industrial occurrence. These may include wetter weather, different vegetation phenology, industrial operating conditions and changes in the dispersion of the air.

The system became intermediate in 2025. NDVI decreased from the outstanding value observed in 2024 (0.3550) to 0.3490, while LST increased to 39.31 °C. NO₂ showed a slight increase while SO₂ was observed to be the lowest since the beginning of the series. The significance of the combination is that it demonstrates that the SO₂ reduction continued despite the fact that there was some apparent vegetation and thermal reversal. This decoupling reinforces the case for considering air-pollution management and land-surface management as interdependent but separate aspects of urban sustainability.

In all of the 6 years, thus, 2 patterns are stronger than any simple linear pattern. The first is the opposite movement of NDVI and LST, which is physically sound and validated by the correlation analysis. The second is the fact that NO₂ displays different behavior than SO₂, which means that “industrial air pollution” can not be considered as a single variable. The title of the study is industry specific, referring to the context of Temirtau, while the analytical evidence is pollutant specific and scale aware.

Scale of measurement and comparison with previous evidence

It is important to pay attention to the scale of measurements when comparing with the previous studies in Temirtau and Kazakhstan. Starikova and Yaroshenko (2016) studied the surface layer of the atmosphere for pollutants, and detected zones with high industrial impact. Air quality was characterised at the city level based on regulatory and industrial-emission information by Assanov et al. (2021). Kerimray et al. (2020) assessed levels of urban pollutants and their health impacts. Satellite column densities are used instead in the present study. The fact that there is a general consensus on the general characterisation of Temirtau as an environment-stressed industrial city does not imply that the numerical values obtained by these methods are directly comparable.

This separation is vital when it comes to WHO guidelines. Recommended air-quality levels reported by the World Health Organization (2021) are in the form of levels of concentration averaged over specified periods. The NO₂ and SO₂ in this study are given in mol m⁻², which is the amount of a gas integrated through an atmospheric column, that is, Sentinel-5P NO₂/SO₂. To convert these values to surface concentrations one would need to make further assumptions concerning vertical profiles, pressure, temperature and boundary-layer height. This conversion was not made because it may increase the uncertainty rather than decrease it. Thus, the study cannot draw any conclusions regarding adherence to WHO concentrations.

The contribution of the remote sensing is instead comparative and integrative. It enables a comparison of different variables of the atmosphere on the same large spatial area and season as that of the land-surface indicators. This allows for the question to be raised about whether a green summer or a hot summer was connected with a greater or lesser loading of the atmosphere. It is not a regulatory assessment but an environmental systems assessment. In this regard, this method aligns with the economic-ecological analysis conducted by Arifzade et al. (2026), which also focuses on interdependent connections between conditions and urban drivers, instead of using a single indicator.

The publication design is also based in the spatial resolution contrast. To display Sentinel-5P pixels together with Sentinel-2 and Landsat at the same map size, could be tempting to compare the data visually at a higher level of detail than provided in the atmospheric data. The time-series plots are hence a methodological decision which is supposed to be interpretive honest. The maps of high resolution depict the spatial variation of vegetation and surface temperature in 2025, and the plots of the atmosphere depict the time-series of area-mean loading. They combine to convey as much information as possible from each sensor.

Real solutions to manage the environment

A tiered monitoring system is desirable in the development of an evidence-based environmental strategy for Temirtau. The official ground-monitoring network should continue to be the first tier network required for regulatory concentrations, exceedance analysis and public-health communication. A second tier can be based on satellite atmospheric products offering the advantage of providing broad spatial coverage and an indication whether regional temporal trends are consistent with the ground observations. Vegetation, surface heat, disturbed land and environmental status of areas near industry can be monitored with high resolution land imagery at a third tier. Bringing these tiers together would give a comprehensive overview than any individual data source.

In the case of industrial operators, the environmental indicators could be correlated with the operation parameters. Satellite NO₂ and SO₂ could be correlated to monthly steel production, fuel consumption, electricity use, coke-oven activity, maintenance shutdowns and emission-control performance. If there are regular relationships, then Earth-observation information can be used to determine the intervals for in-depth study. Use of this data should be collaborative not punitive: satellite data are most useful when considered alongside, and not in isolation from, verified operational and monitoring data, and should not be used to make inferences of violations based on coarse data.

The NDVI-LST result is more directly applicable to municipal planning. Persistent low vegetation and high surface temperatures in summer can be considered as priorities for urban-greening feasibility studies, shade provision, soil rehabilitation and water sensitive design. It is important to not aim for maximum vegetation everywhere because of constraints on industrial safety, water availability and land function. Spatial planning, on the other hand, can prioritize sites where ecological measures can be taken that have thermal and social advantages, while not being in conflict with industrial activities.

Finance is a key component of implementation. Reducing industrial pollution and enhancing ecological infrastructure is often expensive and has long lifespan of the infrastructure. Projects where there are quantifiable environmental goals could be financed with green bonds, sustainability linked finance, concessional credit, or blended public-private finance. As seen in the wider literature reviewed in this paper, green finance can assist the energy and environmental transition (Mammadov, 2025; Sadiqov et al., 2026). Measurable indicators for Temirtau could be verified reduction of conventional emissions, reduction of energy intensity, rehabilitated land area, urban tree survival and change of heat-prone surface cover.

A single satellite indicator should not, however, be used as a policy target when evaluating policy. Changes of phenology in agriculture outside the urban core can be affecting the NDVI, weather changes can affect the LST, and weather transport can affect Sentinel-5P columns. An environmental performance framework should involve satellite-based data, ground measurements, meteorology, land use data

and industry verified reporting. The utility of the present study is that the satellite component can be applied in a consistent manner and can help to identify patterns that could be useful in the selection of more detailed questions.

The green-economy implication thus is one of integration. Industrial technology, finance, regulation, urban land management and urban public accountability will all be important factors in Temirtau's long-term environmental transition. Environmental indicators can be helpful if they help make those interactions more visible. The multi-sensor framework developed here offers a practical baseline to be updated year by year and extended if more data are available.

Cross indicator synthesis and implication for transition monitoring

The results indicate that the environmental situation in Temirtau can be viewed as a multidimensional trajectory, rather than as a single improving or deteriorating trend, based on the combined analysis of the indicators. The SO₂ series shows the highest improvement since 2022, but NO₂ continues to be volatile and is still higher than it was in 2020. There is significant interannual variability in vegetation and LST, but no significant monotonic trend. If a monitoring system only communicated the decrease in SO₂, it therefore could give a more consistently positive picture than the full set of data would. However, just looking at the 2023 heat and low NDVI would underestimate the 2024 strong reversal.

The implications of this observation on the evaluation of environmental transition are significant. Sustainability goals for industries can typically be based on quantifiable emissions or energy reduction, and municipal environmental initiatives can be based on heat mitigation, greening, or land rehabilitation. The rate of progress towards these targets can vary. The Temirtau series is an example of which helps to explain why a set of individual indicators might be more important than a composite indicator. Diagnostic information is captured in separate indicators, which enables policy makers to consider the following: If one domain is getting better, is another staying the same or getting worse?

A good example is the SO₂ decline of 2022-2025. The satellite signal may be thought of as evidence of reduced sulfur loading if it is backed up by future ground monitoring and verified industrial inventories that indicate the same trend. If it is not in agreement with the ground data, then the difference alone would be useful, and would drive an investigation of the meteorology, vertical distribution or retrieval quality. Satellite observations thus have a role to play both when they support official information and when they raise questions about apparent discrepancies. This triangulation is more scientifically defensible than relying on one source as the ultimate source of authority.

The monitoring value of the relationship between NDVI and LST is different because both are based on observation of the land surface at relatively fine spatial resolution. The strong inverse relationship is evident over this short time series; if continued over a longer time series, it would give a clear basis for evaluation of the thermal benefits of urban vegetation. In order to assess changes in target greening areas versus control areas before and after intervention, intervention studies could be conducted with target greening areas and control areas before and after, using the same logic as the summer composite. The main drawback of the citywide annual correlation employed here is that it is less able to measure policy impacts than is such a quasi-experimental design.

Caution is needed with the pollutant-vegetation relationships. Annual mean NDVI is affected by many variables such as land management,

crop cycles, precipitation and irrigation and atmospheric pollution can have an impact on vegetation physiology. Furthermore, the 15 km buffer includes peri-urban land which might not react in the same way as urban trees and parks. Thus, the negative NO₂-NDVI coefficient should be interpreted as a sign that further spatial and temporal analysis of the data is warranted rather than as a sign of NO₂-induced vegetation damage. This separation has to be communicated explicitly in any policy communication on the basis of the study.

The presence of structural breaks should also be taken into account for transition monitoring. A single change in the indicators can mean a change in ownership, a large investment in new equipment, a change in fuel type, an economic recession, a very wet summer or a severe drought. A 6-year period cannot be used to determine stable breakpoints, however, the prominent SO₂ peak in 2022 and the NDVI/LST reversal in 2024 illustrate that single years beyond the norm can be driving simple trends. Increasing data size will enable methods like segmented regression, Mann-Kendall trend testing or intervention analysis to yield better evidence of ongoing environmental change.

An additional benefit of the framework is communication. The maps of vegetation and surface temperature will be easily understood by planners and the public, and pollutant time series can be used to represent general trends in atmospheric change without giving the impression of neighborhood precision. When these different types of evidence are considered together across Figures 1-4, the multi-scale nature of environmental monitoring in the city becomes apparent. It also clarifies the reason why there are different sensors for different questions. This transparency is crucial if remote sensing is to serve as a means to gain public confidence, and not as a black box exercise.

The most valuable use of the framework from a green-economy point of view could be as an evidence layer for prioritizing and evaluating investments. There is a growing need for measurable outcomes in the financial world of the environment. Satellite products can provide additional evidence for land rehabilitation, vegetation recovery and thermal change; with atmospheric products providing wider screening of emission related trends. They can be used in conjunction with audited project metrics but not alone. In this way, the Earth observation can help to bridge the gap between the scientific monitoring and accountability requirements of an environmental investment.

The general message is thus well-balanced. The study finds a positive decrease in SO₂ after 2022 and a good relation between the vegetation and temperature, while NO₂ and vegetation remained variable. Based on this short series, it is not possible to give the impression that the environmental transition in Temirtau is "full" improvement or "steady" deterioration. A more defensible interpretation is that various aspects of the urban-industrial environment are undergoing change at varying rates, and continued monitoring is needed to ascertain whether these changes are established trends.

Implications for industrial ecology and green economy

The results have several implications for the environmental management in Temirtau. First, the significant inverse relationship between vegetation-temperature indicates the need to consider land-cover management in the context of an industrial-city sustainability strategy. Urban greening, the rehabilitation of disturbed land, the protection of existing green corridors and better management of peri-urban vegetation can help to control temperature, although they cannot replace the control of industrial emissions. This interpretation is in line with the overall thesis that

green-city policies can achieve co-benefits on environmental quality and public welfare (Qadimli & Mammadov, 2026b).

Second, the air quality findings illustrate the need for measuring industrial modernization using more than a single pollution indicator. Unlike with SO₂, NO₂ did not follow the same trend and the large reduction in SO₂ after 2022 could not be correlated with a similar reduction in NO₂. Various combustion processes, technologies, fuel properties and atmospheric behaviors are correlated to different pollutants. Hence, a transition strategy designed to consider a single pollutant may ignore key aspects of the industrial environmental performance. Regulatory observations from ground-stations should continue to be the first point of call, with Sentinel-5P serving as a consistency check at regional level and to study the temporal evolution over a large temporal period.

Thirdly, improving the environment in a heavy industry city is an economic aspect. There is a need for capital for industrial decarbonisation, energy efficiency improvements, greener process technologies, renewable electricity and rehabilitation of land. When considering the green economy, it is important to highlight the need to make environmental projects a part of development policy, and not to think of them as external costs (Qadimli & Mammadov, 2025). Green finance can contribute to mobilizing investments for such transitions. Mammadov (2025) highlights the role of public perception and awareness of green finance and Sadiqov et al. (2026) illustrate the use of financial instruments in renewable-energy financing. For Temirtau, similar processes may apply in relation to the modernization of energy and environmental infrastructure of industry, modernization of environmental protection facilities in the cities.

Fourth, the study enables to recognize an ecosystem based interpretation of industrial urban planning. In a different context, Qadimli and Mammadov (2026a) highlight the economic importance of ecosystem sustainability. In Temirtau, the factors are different, but the same: vegetation, water, soil condition, air quality are assets that provide for the long-term performance and attractiveness of urban system. Environmental performance, wellbeing of workers, communities and the ability of infrastructure to meet the demands of low carbon policies are becoming more important drivers of industrial competitiveness. Some of these conditions can be tracked in an evidence layer in a transparent way using satellite indicators.

The results are put into perspective by comparison to previous Kazakhstan studies. Arifzade et al. (2026) found correlations between the particulate pollution and industrial and transport factors in Almaty and Sumgayit, which highlighted the role of socioeconomic factors in urban pollution. The air-quality problem in Kazakhstan is structurally linked with the industrial and energy systems, as demonstrated by Assanov et al. (2021) and Kerimray et al. (2020). A similar ground-based or health-impact analysis is not repeated here for the current Temirtau study. Instead it provides a satellite view, which puts atmospheric indicators into the context of vegetation and surface temperature. The contribution is thus integrative and not regulatory.

Drawbacks of methodologies should also be taken into account when interpreting the results. The first constraint is the 6-year yearly sample. More lagged or seasonal modeling would be possible with a longer period or monthly observations, which would produce greater statistical power. The second is "spatial-scale mismatch. Urban land surfaces are much more finely resolved with Sentinel-2 and Landsat, than with Sentinel-5P atmospheric products. The third is lack of meteorological parameters (precipitation, wind speed, direction, humidity and boundary layer height). The fourth is the use of a circular analytical boundary, instead of defined municipal limits. The

fifth is that annual mean NDVI fails to differentiate between the grassland, agriculture and urban parks or other vegetation types.

It will therefore be logical to expand the workflow in a number of directions for future research. The aggregation to monthly or biweekly periods may be helpful in boosting the number of observations available and may permit partial correlation or regression models using meteorological covariates. NO₂ and SO₂ data from satellites could be compared to official industrial production or emission-inventory data to check the consistency of the change in satellite data with production changes. The classification of land-cover information may be used to separate urban green space from agricultural and semi-natural vegetation. Ground monitoring could be used to evaluate the temporal correspondence between column densities and surface concentrations. Lastly, spatially explicit urban planning analysis could be used to prioritize neighborhoods with both low vegetation and high surface temperature with high population exposure.

Even with these drawbacks, the whole picture framework has useful points. It takes advantage of readily available satellite archives, it can be reproduced in Google Earth Engine and generates additional indicators that can be easily updated when new data is available. These repeatable environmental screening can feed a green-transition monitoring system, where industrial emissions, urban greening and thermal conditions are monitored simultaneously. The results are not a substitute for detailed environmental impact assessment, but could assist in prioritising areas for detailed environmental impact assessment and investment.

CONCLUSIONS

This study evaluated the correlation between industrial air pollution indicators, vegetation cover and land surface temperature with multi-sensor Google earth Engine workflow for the summers of 2020-2025 in Temirtau, Kazakhstan. Harmonized Sentinel-2 NDVI, Landsat 8/9 surface temperature, Sentinel-5P tropospheric NO₂ and SO₂ column densities were analyzed together in the same analytical zone of 15 km. As seen from the resulting series, the recent environmental conditions of the city of Temirtau do not have a direct trend. The vegetation started decreasing in 2020 and continued in 2021, 2022, and 2023 before making a sharp increase in 2024 before decreasing slightly in 2025. The surface temperature evolved in a fairly contrary fashion, with a maximum for the 6-year period in 2023 and a minimum in 2024. Both NO₂ and SO₂ exhibited some fluctuations, with a peak in 2021 and 2023 for NO₂ and a distinct peak in 2022 for SO₂ followed by a notable decline through 2025.

The most significant statistical finding was the very high inverse correlation between NDVI and LST ($r = -0.797$, $p = .057$). Though the p value was still slightly above the conventional .05 value, the magnitude and year-to-year trend clearly suggest vegetation-thermal coupling, which is also apparent in the 2025 spatial composites. NO₂-LST and SO₂-LST relationships were positive while moderately to strongly inverse relationship with NDVI ($r = -0.680$) was observed for NO₂. Pollutant relationships were not found to be statistically significant and should be viewed as exploratory signals and not proof of causal relationships.

The research is significant in the context of industrial urban sustainability research by showing how in a transparent and reproducible framework, surface and atmospheric satellite indicators can be combined. The results for Temirtau reinforce two policy strategies – to enhance industrial air-quality management as well as to preserve or increase vegetated areas that can provide summer thermal regulation. These priorities are complementary. Urban greening

cannot make up for any industrial emission and emission-control modernization cannot substitute ecosystem services from vegetation and water-sensitive management. Therefore, industrial modernization, cleaner energy, monitoring of emissions, land rehabilitation and urban ecological planning should all be elements of a green-city strategy.

The findings also have implications for investing in green economy. You need financing schemes that can meet the needs of environmental modernization in a heavy-industry city, including the costs of cleaner process technology, energy efficiency and renewable energy and ecological infrastructure. Satellite monitoring can offer one line of evidence for the assessment of environmental conditions at change over time and identify conditions that may need to be investigated more closely on the ground. In this way, remote sensing should be used to inform regulatory monitoring and investment planning but not as a replacement for them.

The conclusions have some restrictions. The analysis is based on six observations per year, the data from Sentinel-5P are column densities and not surface concentrations, and the data from the atmosphere and the surface are measured at different spatial scales. No meteorological covariates or official production or emission data were used. Future work should, therefore, extend the series, include monthly observations, and include wind and precipitation data, include data from ground-monitoring stations and data on industrial activity, and test multivariate models. The study serves as a useful baseline in these zones for further assessment using satellite data for the environmental transition of Temirtau and other industrial cities of Kazakhstan.

AUTHOR CONTRIBUTIONS

Conceptualization, E.A. and A.Z.; methodology, E.A., A.Z. and Y.Y.; data curation, E.A. and Y.Y.; formal analysis, E.A. and A.Z.; visualization, E.A.; writing—original draft, E.A.; writing—review and editing, A.Z. and Y.Y. All authors have read and agreed to the submitted version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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DATA AVAILABILITY

The satellite source datasets used in this study are publicly available through the Google Earth Engine Data Catalog. The derived annual indicator table and Google Earth Engine processing script are available from the corresponding author upon reasonable request.

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Remote sensing assessment of nature-based solution priorities and green finance needs for ecosystem restoration in Shahdag National Park

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Keywords

Nature-based solutions; remote sensing; ecosystem degradation; Shahdag National Park; NDVI

ABSTRACT

NbS are becoming an ever more critical strategy to restore degraded ecosystems, while also promoting biodiversity conservation, climate resilience and ecosystem services. An integrated remote sensing approach was employed in this study to evaluate the spatial extent of ecosystem degradation and to prioritize the areas for NbS implementation in the Shahdag National Park, Azerbaijan. In Google Earth Engine and QGIS, open access geospatial data was processed to include Sentinel-2 Level-2A imagery, Landsat 8 and 9 Collection 2 Level-2 thermal products, Shuttle Radar Topography Mission (SRTM) elevation data, Hansen Global Forest Change, and the World Database on Protected Areas. Ecosystem conditions were characterized using a suite of environmental indicators such as the Normalized Difference Vegetation Index (NDVI), Normalized Difference Moisture Index (NDMI), Bare Soil Index (BSI), land surface temperature (LST), slope, elevation, and forest cover change. These were combined to create a composite Ecosystem Degradation Index to help determine where restoration should be a priority. Pearson correlation analysis was also used to assess the relationship between vegetation condition and surface temperature. Results showed significant spatial variation throughout the national park, characterized by decreased vigour of vegetation, diminished availability of moisture, and greater bare-soil exposure and surface temperatures in certain landscape units. The correlation between NDVI and LST was moderate ($r = -0.567$, $p < 0.001$) and was statistically significant, which means that higher vegetation density is associated with lower LST. The estimated forest cover in 2000 is about 83,184.15 ha with a projected loss of 279.8 ha of tree cover between 2001 and 2025. Created maps offer a practical spatial framework for prioritising ecosystem restoration and for protected-area management. The proposed procedure illustrates the benefits of combining freely available satellite observations and geospatial analyses in evidence-based NbS planning in mountain protected areas and provides a replicable approach for comparable mountain landscapes in the South Caucasus. The results also aid in the development of sustainable environmental management and green development strategies in Azerbaijan, for data-driven conservation decision-making.

INTRODUCTION

Protected Areas in the Mountains are vital to the provision of ecosystem services, such as biodiversity conservation, water regulation, soil protection, climate regulation, recreation and livelihood support. But, the degradation of vegetation, exposure of soil, moisture stress, erosion, forest disturbance and alteration of thermal environment has grown increasingly common in such ecosystems. In mountainous regions, these pressures are particularly relevant, as steepness, large altitude gradients and difficult access make ecological monitoring and ecological restoration planning difficult (Cohen-Shacham et al., 2016; IUCN, 2020).

NbS have become a key strategy that helps solve ecosystem degradation and provide benefits to biodiversity, climate resilience, and human health and well-being. Some of these activities in mountain protected areas may be forest regeneration, grassland creation or rehabilitation, erosion control, riverbank stabilization, watershed rehabilitation or tourism and grazing management. To effectively implement the strategy, spatial data is needed, indicating where ecological stress accumulates and where restoration should take priority.

Although the field surveys are essential to determine the health of an ecosystem, this can be challenging in large, topographically diverse areas. This is complemented by remote sensing, which allows for repeat measurements and spatial consistency for vegetation cover, moisture, land surface temperature, terrain, bare soil exposure, and change in forest cover. Large amounts of satellite data can also be processed and integrated efficiently using Google Earth Engine and geographic information systems for assessment and planning of environmental restoration.

The vegetation condition is often measured by using the Normalized Difference Vegetation Index (NDVI). Using the red and near-infrared reflectance, NDVI is calculated and widely used as an indicator of vegetation's greenness, density, and photosynthetic activity. A higher value generally signifies a denser vegetation whereas a lower value can relate to sparse vegetation, exposed soil, rocky terrain or degraded land (Rouse et al., 1974; Tucker, 1979). NDVI must also be considered alongside other environmental indicators as it is not a standalone indicator of ecosystem health.

The Normalized Difference Moisture Index offers more information on vegetation and surface-moisture conditions. It is especially helpful

in the identification of dry vegetation, moisture stress and areas of decreased ecological resilience. Combined with NDVI, NDMI can be used to enhance the separation of healthy vegetation and dry vegetation, sparsely vegetated areas and exposed surfaces in mountain environment (Gao, 1996).

Exposure of bare soil and the temperature of the land surface are other markers of degradation. Varying degrees of vegetation cover and bare ground can create a situation of increased erosion, runoff and moisture loss. Bare and dry surfaces will also absorb more solar energy and vegetated areas tend to be cooler due to shading and evapotranspiration. Thus, negative NDVI-LST relationships can be helpful in the detection of vegetation induced cooling and thermal stress (Weng et al., 2004; Yuan & Bauer, 2007).

In the mountain zones the ecological conditions are strongly shaped by the topographic conditions. Elevation has impacts on temperature, precipitation, vegetation zones, growing seasons, slope has impacts on water movement, soil erosion, accessibility, feasibility of restoration measures. Combining elevation and slope with vegetation, moisture, temperature and bare-soil indicators allows for better insight into the ecological vulnerability and selection of ecological solution approaches.

One other crucial factor of the ecosystem evaluation is long term forest-cover change. Global forest data derived from Landsat can be used to detect tree cover and annual changes in tree cover for long time series. These data can show spatial patterns of disturbance, but the loss of tree cover does not necessarily mean an end-of-ecosystem loss, as it can also result from fire, disease, wind damage, harvesting or temporary ecosystem disturbance (Hansen et al., 2013).

Shahdag National Park is among the significant mountain protected areas of Azerbaijan. It has a high ecological variety of forests, alpine and subalpine vegetation, river systems and exposed mountain surface and high relief. These attributes also result in varying spatial sensitivities to vegetation stress, soil erosion, moisture loss and forest disturbance. So far, there is insufficient research that combines the variables of vegetation, moisture, temperature, terrain, bare-soil and forest-change indicators within Shahdag National Park, even though satellite data is available.

The ecological state of the Park is also related to wider socioeconomic and environmental-development concerns. Tourism and recreation, water protection and local economy are dependent on healthy mountain ecosystems. The previous studies in Azerbaijan have shown the significance of combined use of environmental indicators with economic and human pressure indicators for assessing ecological risks (Arifzade et al., 2026). Long-term ecosystem restoration requires effective institutional coordination, transparent reporting, fiscal stability, and reliable accounting and monitoring mechanisms, particularly where environmental interventions must be sustained over several years (Guliyeva et al., 2021; Valiyev et al., 2021).

Recent study results also show that environmental, remote sensing and socio-economic data are all useful in the evaluation of ecological pressures and sustainable development priorities. The analysis of urban growth in Luanda, based on satellite data, revealed a strong relationship between the evolution of vegetation cover and the spatial distribution of surface heat, emphasizing the potential of using satellite-derived vegetation and thermal information for urban environmental stress detection (Qadimli & Mammadov, 2026). Comparable correlations between industrial air pollution and vegetation cover and surface temperature have been examined in Temirtau; comparative evidence from Sumgayit and Almaty has shown the importance of taking into account the pressures from

industrial and transport sectors in environmental assessment (Arifzade, Zhumazhanov, et al., 2026; Arifzade, Mammadov, et al., 2026). Aquatic and coastal ecosystems are also under environmental pressure, as microplastic pollution has been linked to various anthropogenic pressures throughout the Caspian Sea Basin (Mammadov et al., 2026). An economically sound approach to solving these environmental problems, as demonstrated in research on green finance instruments for the development of renewable energy in Azerbaijan (Sadiqov et al., 2026), can increasingly depend on the financing mechanisms that can direct investment towards activities that are beneficial for the environment.

Green finance can play a role in implementing restoration and conservation interventions, including monitoring systems, reforestation, erosion and watershed rehabilitation, and sustainable tourism infrastructure. The studies on Azerbaijan have highlighted the importance of enhancing green finance mechanisms and integrating climate and environmental concerns into economic activities (Qadimli & Məmmədov, 2026; Sadiqov et al., 2026).

To support the interpretation of ecosystem conditions in remotely sensed data, field observations and photographs were gathered inside of Shahdag National Park. The photographs illustrate typical forested, grassland, bare soil, rocky and probable degraded sites. They offer the visual evidence in context and enable comparisons of mapped patterns with real landscape situations. But they are not a statistically representative ground-validation data set; they are used as supporting field data.

The spatial outputs analysed in this study were gathered in the open dataset Remote sensing-derived maps of ecosystem condition and degradation in Shahdag National Park, Azerbaijan (Mammadov, 2026). The data set contains maps of the study area, elevation, slope, NDVI, NDMI, LST, bare soil degradation, vegetation degradation, ecosystem degradation, forest-cover change and vegetation cover surface temp relation.

In this context, the present study is aimed to estimate condition and degradation of the ecosystem in Shahdag National Park by integrated remote-sensing, GIS and field observation approach. Specific objectives are to assess topographic characteristics, vegetation condition, moisture status, land surface temperature, bare-soil exposure, ecosystem degradation and forest-cover change; assess the relationship between NDVI and land surface temperature; and identify areas that may warrant priority action for nature-based restoration. The results are designed to help in the management of protected areas, the restoration of ecosystems, and evidence-based green development planning in Azerbaijan.

LITERATURE REVIEW

For those regions that are difficult to monitor in the field, like protected areas or mountain regions, remote sensing has become an important methodological approach for the evaluation of ecosystem condition and land-cover dynamics and environmental degradation. Satellite observations allow vegetation conditions, water availability and thermal properties together with changes in land-use to be monitored on more or less equally large areas. With the growing availability of multispectral satellite imagery and cloud-based geospatial platforms, remote sensing has grown even more useful for ecosystem monitoring and conservation planning (Pettorelli et al., 2014; Gorelick et al., 2017). In this context vegetation indices like the Normalized Difference Vegetation Index (NDVI) can still be used for vegetation density and condition detection, and moisture-sensitive vegetation indices like the Normalized Difference Moisture Index (NDMI) can be used to extract complementary information relative

to vegetation water content and ecosystem moisture conditions (Rouse et al., 1974; Gao, 1996).

Vegetation indicators can be combined with land surface temperature (LST) to give an other basis for interpretation of ecological stress. Past remote sensing studies have shown that the surface thermal conditions and the vigor of vegetation are well correlated, with the highly vegetated surface having a lower surface temperature, as compared with the sparsely vegetated or exposed surfaces (Weng et al., 2004; Yuan & Bauer, 2007). In a recent study, researchers analysed various levels of urban expansion in Luanda and revealed how surface heat distribution is related to vegetation patterns, highlighting the joint analysis of these three factors as an invaluable tool to assess spatial environmental pressures (Qadimli & Mammadov, 2026). Urban ecosystems are very different from those found in protected mountain ecosystems but the overall methodological approach (combining vegetation measurements with thermal measurements) is applicable to assessing ecosystem condition.

Changes in land-cover/land-use may also be affecting stress in the environment as noticed by some of the satellite observations. The TEMIRTATAU study has focused on the connections between industrial air pollution, vegetation cover and surface temperature, demonstrating the possibilities of multi-environmental indicators for determining the spatial patterns of industrial pressure (Arifzade, Zhumazhanov, et al., 2026). The ecological importance of present pollution forces related industrial and transport is similarly emphasized in Sumgayit and Almaty (Arifzade, Mammadov, et al., 2026). However, anthropogenic pressure is not only relevant for terrestrial ecosystems; evidence from the Caspian Sea Basin can also be found systematically, revealing the relevance of human activities to the contamination and degradation of coastal environments with microplastics (Mammadov et al., 2026). Typically, the conclusions drawn from all these studies stress a multiple dimension understanding of environmental degradation, without a single ecological indicator.

Long-Term Forest-cover Information is another important part of the ecosystem information. Satellite data at the global scale has significantly enhanced capability to detect loss of 'tree cover' and describe forest dynamics over long time scales (Hansen et al., 2013). But when there is a loss in tree cover, it is not automatically interpreted as deforestation, as the loss of tree may be a result of one or several anthropogenic and natural processes. This distinction is of great significance especially in protected mountain areas where related to some site processes (like erosion, landslides, climatic variability, fires, other disturbances) vegetation modification may occur. Therefore, the information on forest change provided by satellites is best used in conjunction with other data derived from vegetation, moisture, temperature, terrain and field observations.

More and more these monitoring approaches are relevant in the implementation of nature-based solutions (NbS). NbS can offer a blueprint that enables ecosystem conservation and restoration to serve both ecosystem protection and climate and broader societal benefits (Cohen-Shacham et al., 2016). The IUCN Global Standard also highlights that it is important that NbS actions should be based on specific societal and ecological problems, located at an appropriate spatial level and that monitoring and adaptive management should be integrated (IUCN, 2020). Hence, for degraded mountain ecosystems there are a number of potentially different interventions that can vary locally, and range from assisted natural regeneration, to erosion control, to vegetation restoration, to riparian rehabilitation, to disturbance reduction, and/or ongoing ecological monitoring. This

can be accomplished by using remote sensing to identify areas of ecological stress as measured by multiple indicators, and where ecological restoration actions may therefore be more likely to be of high priority.

Financial resources need to be available as well and allocated efficiently for ecosystem restoration to be effective. Spatial prioritization is thus not just an ecological exercise, but could also serve an investment planning context, with the objective of finding out where it is most needed to spend money for restoration. Environmental cost-benefit analysis offers a framework for synthesizing the costs and benefits of restoration and delivery of ecosystem services over time, but there are significant potential uncertainties where locally verified cost units and valuations of ecosystem services are not available (OECD 2018). In these cases, scenario based estimates can be used to give an initial financial planning slab than an investment appraisal.

Green finance can influence and take steps to improve the implementation of conservation and restoration programmes in order to make available to capital for environmentally beneficial interventions. The experience in Azerbaijan shows the applicability of green financial instruments to facilitate environmentally-friendly investment, especially in the field of renewable-energy. Larger, public environment investment, green bonds, concessional finance, biodiversity and climate funds, grants and public-private partnership can, potentially, aggregate to finance ecosystem restoration. This becomes more significant as the resources that are available to fund NbS is not yet on the level needed to meet the international objectives of biodiversity, climate and land-restoration (UNEP, 2026).

Although these advances have been made, there is a critical research gap that has not yet been addressed – linking the remote-sensed degradation assessment and the NbS spatial prioritization and indicative green-financing demands in one protected-area framework. Previous assessments often approach monitoring the ecology, change in land-use, planning for restoration, or financing of environmental projects independently. This is especially pertinent for the ecology of shahdag national park, since expected ecological status changes within a park with so much mountainous area makes a combined assessment with field-based monitoring more useful. To fill this omission, the present study combines NDVI, NDMI, LST, bare-soil indicators, long-term tree-cover change and an Ecosystem Degradation Index and field photographic observations to enable the identification of priority areas for restoration, before connecting priority areas identified to scenario-based estimates of restoration financing and potential economic benefits.

MATERIALS AND METHODS

Study area

Shahdag National Park is situated in the Greater Caucasus Mountains of northern Azerbaijan, and is the largest national park in Azerbaijan. Shahdag National Park covers approximately 130,508.1 ha (1,305.1 km²) and includes high-altitude areas, rocky terrain, river valleys, broadleaf forests and alpine meadows. There is a large elevation differential within the park that results in significant temperature, precipitation, vegetation composition and ecological differences. Because of this environmental heterogeneity, Shahdag National Park offers a suitable case study for the evaluation of ecosystem degradation and selection of the priorities for nature-based restoration.

The spatial extent of the study area was acquired from the World Database on Protected Areas (WDPA) and manipulated in QGIS 3.40. To achieve consistency between the environmental indicators, all remote sensing analyses were limited to the park boundary. The

geographical location and the spatial extent of the study area is shown in figure 1.

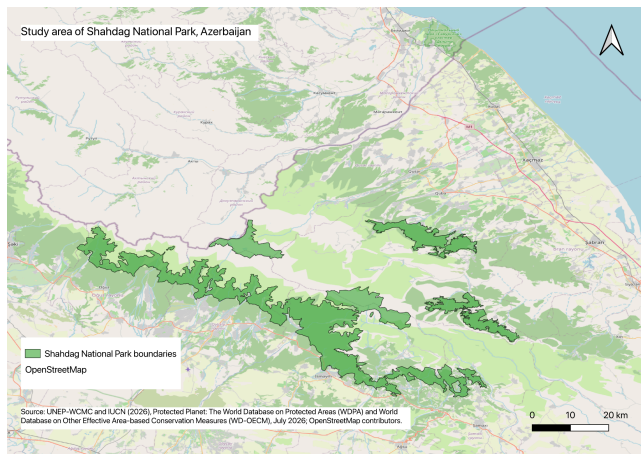


Figure 1. Location and spatial extent of Shahdag National Park, Azerbaijan.

The research design and the source of data are as follows:

This study was conducted as a combination of remote sensing and GIS based ecosystem assessment to determine the areas of Shahdag National Park that may need restoration. Analytical framework included topographic, vegetation, moisture, thermal, bare-soil and forest-cover indicators from freely available satellite and geospatial data.

For vegetation and moisture analysis, the data used included Sentinel-2 Level-2A imagery, while for land surface temperature analysis, Landsat 8 and Landsat 9 Collection 2 Level-2 products were used, and for elevation and slope analysis, Hansen Global Forest Change Version 1.13 and the World Database on Protected Areas were used for the park boundary. Image processing and index calculations were done using Google Earth Engine and map preparation and cartographic visualization were done using QGIS 3.40 (Gorelick et al., 2017; Hansen et al., 2013). Table 1 summarizes the datasets used in this study.

Table 1. Geospatial datasets used in the study

Dataset	Source	Spatial resolution	Purpose
Sentinel-2 Level-2A	ESA Copernicus	10–20 m	NDVI, NDMI, BSI
Landsat 8/9 Collection 2 Level-2	USGS/NASA	30 m	Land surface temperature
SRTM GL1 DEM	NASA	30 m	Elevation and slope
Hansen Global Forest Change v1.13	University of Maryland	30 m	Forest cover and tree-cover loss
WDPA	UNEP-WCMC & IUCN	Polygon	Study area boundary
OpenStreetMap	OpenStreetMap contributors	Vector	Reference basemap

Image preprocessing

All satellite image processing was performed with Google Earth Engine (GEE) which is a platform that allows large geospatial datasets to be processed in the cloud (Gorelick et al., 2017). Surface reflectance products derived from Sentinel-2 Level-2A data were used for vegetation, moisture and bare-soil indicators, whereas land surface temperature analysis was carried out using Landsat 8 and Landsat 9 Collection 2 Level-2 products.

Excessive cloud cover was avoided by excluding scenes from the analysis, while cloud contaminated pixels were masked with the quality-assurance bands supplied with the original datasets to improve

the quality of the images. Residual atmospheric noise and short term temporal variability was then removed by creating median images from these composites. For avoiding spatial inconsistencies between the layers, all the raster layers were clipped to the Shahdag National Park boundary prior to further analysis.

Where needed, the Digital Elevation Model was resampled to ensure it was compatible with the other spatial data. In order to conduct subsequent analyses and map creation all raster products were projected to a common coordinate reference system. The final cartographic layouts were created in QGIS 3.40.

Topographic analysis

The topographic characteristics were analysed using a digital elevation model (DEM) of 30 m spatial resolution from NASA Shuttle Radar Topography Mission (SRTM GL1). The elevation was done using the words elevation of the study area, and the slope was calculated from the DEM using the QGIS terrain-analysis tools.

Ecological processes in mountain regions are strongly influenced by elevation and slope due to their effect on temperature, precipitation, soil development, vegetation distribution, runoff and erosion. Therefore, both were used as ancillary parameters in the interpretation of vegetation condition and ecosystem degradation trends. The elevation and slope maps that are created are given in Figures 2 and 3.

Vegetation and moisture assessment

The Normalized Difference Vegetation Index (NDVI) was used to assess vegetation condition and the Normalized Difference Moisture Index (NDMI) to assess vegetation and surface moisture. The calculation of both indices was performed by using Sentinel-2 Level-2A data in Google Earth Engine (GEE). NDVI was calculated as:

$$NDVI = \frac{NIR+Red}{NIR+Red}$$

where NIR represents the near-infrared band (Band 8) and Red represents the red band (Band 4) (Rouse et al., 1974).

NDMI was calculated as:

$$NDMI = \frac{NIR-SWIR}{NIR+SWIR}$$

where SWIR corresponds to Sentinel-2 Band 11 (Gao, 1996).

Higher NDVI values indicate healthier and denser vegetation, whereas lower values generally represent sparse vegetation, exposed soil, or rocky surfaces. Similarly, higher NDMI values indicate greater vegetation moisture, while lower values suggest drier environmental conditions and potential vegetation stress. The resulting NDVI and NDMI maps are presented in Figures 4 and 5.

Land surface temperature analysis

Land surface temperature was extracted from Landsats 8 & 9 Collection 2 Level 2 data in Google Earth Engine. The surface temperature band was retrieved from the Landsat product and transformed from the scaled to the Kelvin temperature, and then to the C scale, using a scale factor and offset described in the product documentation. The conversion was done in the following way:

$$LST = (ST \times 0.00341802) + 149.0 - 273.15$$

where ST is the value of Landsat surface temperature band. Subtracting 273.15 is to convert the temperature from Kelvin to degrees Celsius.

The images were combined into a median composite, excluding cloud affected pixels. The obtained LST layer was then clipped to the

boundary of the Shahdag National Park. A higher LST was considered as relatively warmer surface which could be correlated with bare soil, rocks and low evapotranspiration and/or low vegetation cover. Figure 6 shows the spatial distribution of land surface temperature.

Bare-soil and vegetation degradation assessment

Bare soil conditions were estimated using the Bare Soil Index (BSI) obtained from surface reflectance data of Sentinel-2. BSI is a composite of visible, near-infrared, and shortwave-infrared bands to separate bare and sparsely vegetated surfaces from the areas of denser vegetation.

The index was obtained by:

$$BSI = \frac{(SWIR+Red)-(NIR+Blue)}{SWIR+Red+(NIR+Blue)}$$

For Sentinel-2 imagery, SWIR, Red, NIR, and Blue correspond to Bands 11, 4, 8, and 2, respectively.

Positive BSI values are typically reflective of bare soil or rocky surfaces and low values are generally indicative of vegetated or moisture-rich sites. The BSI was not interpreted independently due to the possibility that high BSI values occur naturally in rocky mountain terrain. It was assessed along with NDVI, NDMI, LST, elevation and slope.

Vegetation degradation detection was done in the regions with relatively low NDVI, low NDMI and high BSI. The joint effort lowered the chances of a natural exposed mountain slope being considered only a degraded area. A map of bare-soil and vegetation degradation is produced and displayed in Figure 7.

Ecosystem Degradation Index

An integrated Ecosystem Degradation Index (EDI) was created to pinpoint where several ecosystem degradation indicators coincided. The vegetation condition was incorporated in this index along with moisture status, land surface temperature and bare soil exposure.

The raster layers were normalized to a common scale 0-1 prior to integration. The NDVI and NDMI were converted to inverse to reflect better conditions of the ecosystem with higher vegetation and moisture values. LST and BSI were directly used as higher values may represent thermal stress and higher surface exposure.

The index was calculated as:

$$EDI = \frac{(1-NDVI_n)+(1-NDMI_n)+LST_n+BSI_n}{4}$$

where n is the normalized value of each indicator.

Areas with higher EDI values are areas with low vegetation density, low moisture, high surface temperature, and no or low ground cover. The lower values represent relatively stable ecosystem conditions. The index was not intended to be a measure of irreversible degradation, but a tool for screening possible areas of priority for restoration.

For cartographic interpretations the final EDI values were placed in relative degradation categories. The spatial distribution of the ecosystem degradation is shown in Figure 8.

Forest-cover change analysis

The Hansen Global Forest Change v1.13 data with 30 m spatial resolution was used for the forest-cover change assessment. The dataset includes data for the extent of tree cover in 2000, as well as for annual tree-cover loss for the following years (Hansen et al., 2013).

The area of tree-cover was cropped to the boundary of the Shahdag National Park. The forested areas were mapped based on the percentage of tree-cover value in the dataset and the annual loss layer

was used to identify areas where some degree of tree-cover disturbance took place in the observed period.

Tree-cover loss was interpreted with caution as it could be a result of fire, wind damage, disease, timber removal, or other types of disturbances. Hence, the layer obtained was not used to label all the detected loss as a permanent deforestation. Figure 11 shows the final forest-cover change map.

NDVI–LST relationship

Pearson's correlation coefficient was used to determine the relationship between land surface temperature and the condition of the vegetation. The NDVI and LST raster values were extracted from the sample locations in the national park at the same spatial location.

The Pearson's correlation coefficient was determined to be:

$$r = \frac{\Sigma(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\Sigma(x_i - \bar{x})^2 \Sigma(y_i - \bar{y})^2}}$$

where:

- x_i represents NDVI values;
- y_i represents LST values;
- $\bar{x}$ and $\bar{y}$ represent the mean NDVI and LST values;
- r represents the correlation coefficient.

A negative correlation indicates that locations with denser vegetation generally have lower surface temperatures, while a positive correlation suggests that both variables increase together. The relationship was visualized using a scatter plot with a fitted linear trend line, presented in Figure 10.

Field photographic observations

The field photographs were also gathered at certain points in Shahdag National Park in order to help visualise the patterns observed on the satellite images. The images show various types of terrain, ranging from forests and grasslands to rocky surfaces, bare soil, and areas with potential signs of degradation or erosion.

The photographs were not obtained by a systematic statistical sampling design and therefore, quantitative accuracy assessment were not conducted. These were instead used for contextual comparison and visual interpretation of the environmental indicators mapped.

After the images and associated information are available, the final description of the field observations, including location names, dates and photo details, will be added. The field photographs chosen will be displayed in Figure 9.

The practice of spatial integration and the generation of cartographic products. Each spatial layer was clipped to the same national park boundary and the same interpretation was made for consistency. The NDVI layer was compared with the NDMI layer, LST layer, BSI layer, the elevation layer, the slope layer, the ecosystem degradation layer, and forest-cover change layer visually and spatially.

In QGIS 3.40 the final maps were created, and a standardized set of cartographic elements were added, including:

- title;
- legend;
- scale bar;
- north arrow;
- coordinate reference information;
- study-area boundary;
- data-source statement.

A dataset was compiled containing maps and processed visual outputs during the study (Remote sensing-derived maps of ecosystem condition and degradation in Shahdag National Park, Azerbaijan

(Mammadov, 2026)). The data can be used to make the principal spatial results of the study available independently and transparent to the user.

Financial assessment of restoration priorities

A first financial assessment was created to link the spatial results on ecosystem-degradation with the planning of restoration. The area representing the valid ecosystem degradation in the Ecosystem Degradation Index (raster) was ~118,182.9 ha. EDI values fell between 0.201 and 0.758, and were grouped into five equal interval classes of very low, low, moderate, high and very high relative degradation. High and very high degradation areas were deemed to be priority areas for financial planning for restoration.

To calculate the area in hectares of each degradation class the number of valid raster pixels has been multiplied by their geodesically adjusted pixel area. Forest-cover loss was determined by adding all the pixels that had a loss value between 2001 and 2025. As the data was in a geographic coordinate system, the size of the pixels was adjusted based on latitude and not on the assumption of a constant planar pixel size.

The potential cost of restoration can subsequently be estimated using:

$$TRC = A_R \times C_H$$

where TRC is the total restoration cost, A_R is the restoration-priority area in hectares and C_H is the estimated restoration cost per hectare. Project appraisal may also incorporate net present value and benefit–cost analysis to compare discounted restoration costs with expected ecosystem-service benefits (OECD, 2018).

$$NPV = \sum_{t=0}^n \frac{B_t - C_t}{(1+r)^t}$$

where B_t represents expected benefits, C_t represents costs, r is the discount rate and n is the project assessment period.

Since there were no locally verified restoration unit costs, the financial assessment was based on a scenario. Three indicative unit-cost scenarios were considered: USD 1,000 ha⁻¹ for a low-cost scenario, USD 2,000 ha⁻¹ for a moderate-cost scenario and USD 3,000 ha⁻¹ for an intensive-restoration scenario. These were used as analytical assumptions and not actual market prices. The total restoration financing was estimated as the product of the sum of the high and very high EDI area and the assumed unit cost per hectare. Where costs and benefits of environmental projects are uncertain, scenario analysis will be appropriate and should be viewed in conjunction with field verification and detailed project level appraisal (Organisation for Economic Co-operation and Development [OECD], 2018).

$$TRC_S = A_P \times UC_S$$

where TRC_S is the total restoration cost under scenario S , A_P is the priority area in hectares and UC_S is the assumed unit cost per hectare.

To estimate the potential long-term economic and social benefits of restoration, an indicative benefit–cost ratio ranging from 4:1 to 38:1 was applied. This range reflects international evidence indicating that each monetary unit invested in nature restoration may generate approximately four to thirty-eight monetary units of economic and social benefits. Potential gross benefits were calculated as:

$$TEB_S = TRC_S \times BCR$$

where TEB_S represents the potential total economic benefits under scenario S , TRC_S is the estimated restoration investment, and BCR is the assumed benefit-cost ratio. As this ratio was derived from international evidence rather than a site-specific valuation for Shahdag National Park, the results were interpreted as indicative scenario estimates rather than forecasted financial returns.

RESULTS AND DISCUSSION

Topographic characteristics

When the elevation analysis was carried out, it was found that there was a large altitude difference in Shahdag National Park, which would indicate that the study area has a complex mountainous relief. The lowest point was about [lowest point elevation] m above sea level and the highest point was [highest point elevation] m above sea level. The lowest elevations were predominantly distributed along the river valleys and the peripheral areas of the park while the highest elevations were in the central and northern mountainous areas of the park.

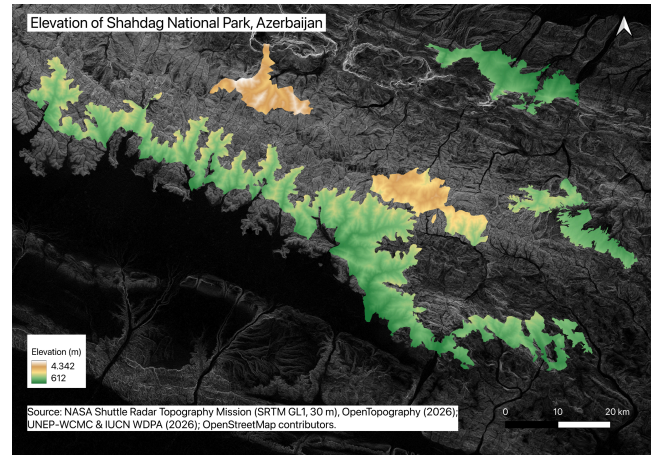


Figure 2. Distribution of elevation in the Shahdag National Park.

There was also significant spatial variation in the slope analysis. Valley floors and lower mountain areas were predominantly characterized by gentle and moderate slopes, whereas high-altitude and strongly dissected terrain was predominantly characterized by steep and very steep slopes. These topographic variations are significant because steep slopes tend to have high surface runoff, high soil erosion, high landslide potential and high disturbance potential to vegetation.

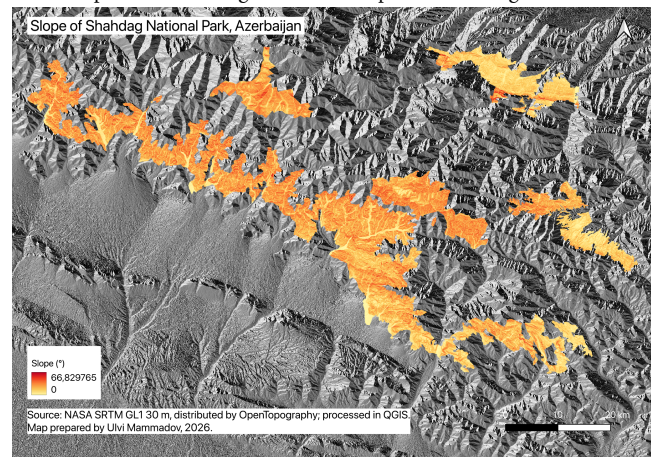


Figure 3. The distribution of slope in Shahdag National Park.

Vegetation condition

The NDVI results revealed that there were spatial variations in the vegetation density in the national park. The areas with higher NDVI were primarily in forests, in river valleys, and in relatively wet mountain slopes. Rocky surfaces, high elevation areas, bare soil and patches with low vegetation and possibly degraded surfaces were correlated with low NDVI.

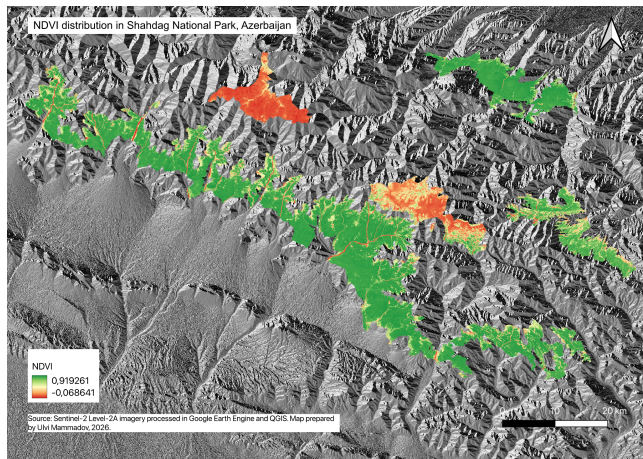


Figure 4. Spatial distribution of the NDVI in Shahdag National Park.

A low NDVI should not be taken to indicate degradation in ecosystems in high altitude regions. A number of these sites are a natural rocky or alpine or low vegetation sites. Thus, NDVI was combined with moisture, temperature, bare-soil, elevation and slope indicators for interpretation.

Vegetation and surface-moisture conditions

Generally, the spatial distribution of NDMI was correlated with the spatial distribution of NDVI. Moisture levels were higher close to areas of relatively high vegetation density and lower in the exposed mountain surfaces and in the areas of low vegetation density.

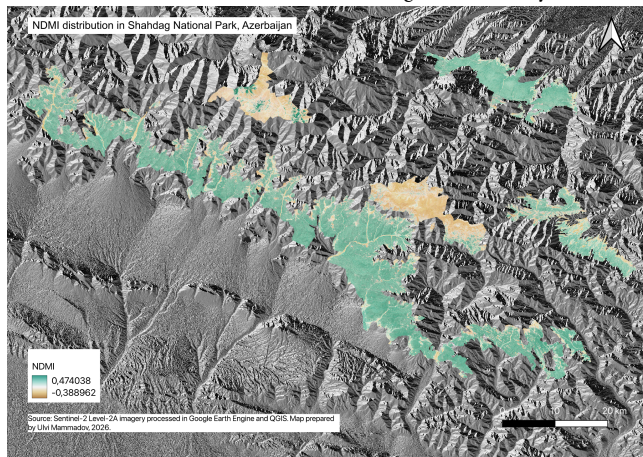


Figure 5. The spatial distribution of NDMI in Shahdag National Park.

Overall, the NDVI and NDMI trends revealed that regions with higher vegetation cover tended to have better moisture levels. However, lower vegetation density often correlated with low moisture availability and high soil exposure.

Land surface temperature

Spatial variations in the land surface temperature were found as significant in Shahdag National Park. Densely vegetated zones, shaded mountain slopes, river valleys and high altitude zones had relatively low temperatures. Exposed areas, areas with sparse vegetation and bare or rocky areas had more surface temperatures.

During the period of observation, the minimum LST observed was about 18.9°C and the maximum LST observed was about 44.3°C. The values are derived from satellite data and are indicative of surface temperatures, not near-surface air temperatures.

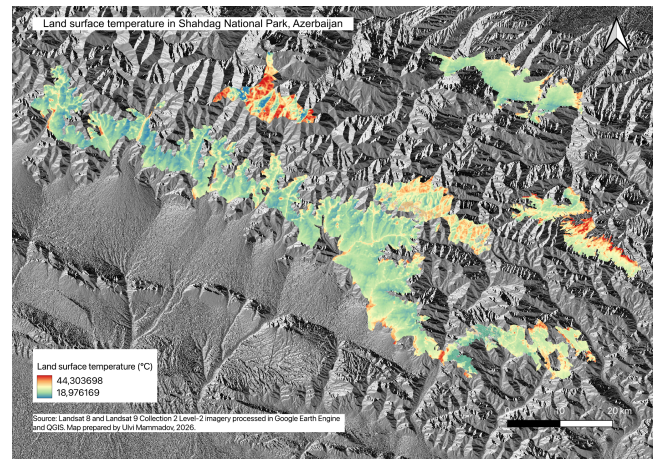


Figure 6. Spatial Distribution of LST of Shahdag National Park.

The spatiotemporal distribution of LST was overall found to be inversely correlated with vegetation cover. There was a relative cooling in forested and moisture rich areas, while exposed surfaces and areas with limited vegetation were warmer.

Exposure of bare soil and loss of vegetation

The bare soil and vegetation degradation assessment found a few areas of bare soil and a rocky site with less vegetation cover and less moisture. An increased bare-soil value was especially evident in high mountain areas, steep slopes, and areas with low vegetation cover.

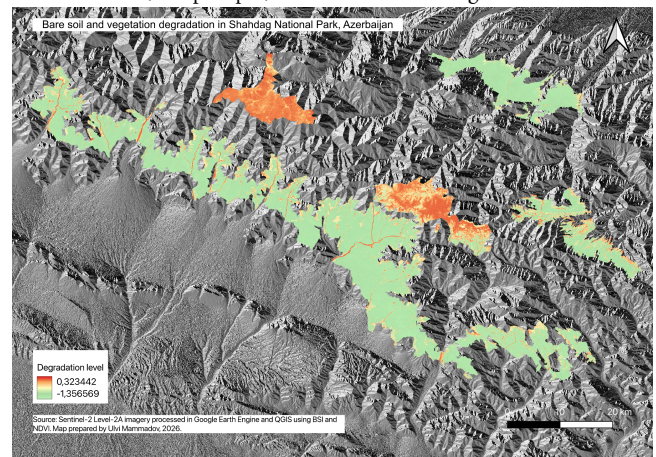


Figure 7. Bare-soil exposure and vegetation degradation index in Shahdag National park.

Regions with high BSI, low NDVI and low NDMI were deemed to be more exposed to vegetation stress, moisture constraint and the threat of erosion. But not all naturally exposed rocky areas were considered degraded based just on high BSI values.

Ecosystem degradation patterns

The Ecosystem Degradation Index identified "hot spots" of low vegetation density, low moisture, high land surface temperature, and high soil exposure. The higher EDI values were primarily found in less-vegetated and exposed locations, with lower degradation values in forested and moisture-rich areas.

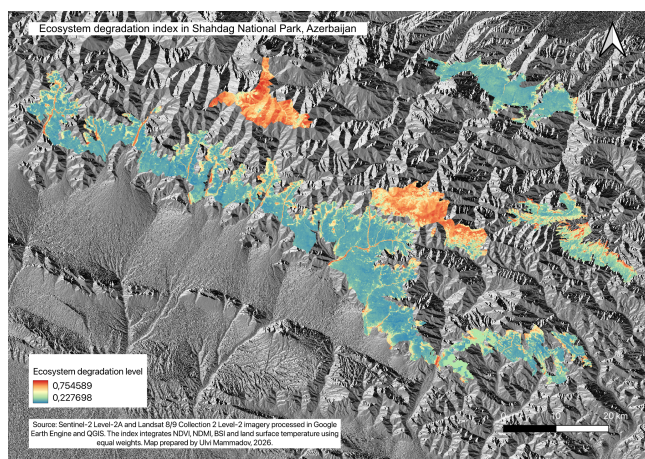


Figure 8. The map of the Spatial distribution of the Ecosystem Degradation Index for Shahdag National Park.

The outcome of the results indicated that not all areas of the national park were equally stressed. There were also some regions that showed relatively stable ecological conditions and other regions that showed some overlap of the indicators of vegetation stress, thermal exposure, moisture limitation, and surface vulnerability.

Priority field assessment may be needed in areas falling within the highest relative degradation category prior to restoration efforts. Depending on the local conditions, any or all of these sites may be appropriate for erosion control, and vegetation recovery and stabilization, forest regeneration, or other NbS.

Field photographic observations

Field observations were conducted next to the villages of Galajig, Istisu, Chaygovushan, Gurbanefendi and Buynuz, which are within or near the borders of the landscape of the Shahdag National Park. The photographs were gathered to support the remote sensing analysis and complement it with visual evidence of vegetation structure, geomorphology, hydrology and heterogeneity of the ecosystems of the study area. Field observations can complement the interpretation of indicators derived from satellite data, as they provide additional context on landscape characteristics that may not be fully conveyed by satellite-derived data (Pettorelli et al., 2014).

Figure 9a illustrates typical forest types such as old-growth broadleaf forests, mixed deciduous forests, extensive ground cover, variable canopy height in different seasons, and regions with varying vegetation cover. The observations broadly agree with regions with relatively high NDVI and NDMI and low land surface temperatures.



Figure 9a. Field photographs representing diverse forest and ecosystem conditions in the upper mountain zone near Istisu, Chaygovushan, Gurbanefendi, and Buynuz villages.
(a) autumn forest on mountainside; (b) mossy broadleaf forest; (c) spring beech

forest; (d) autumn hillside with mixed forest; (e) fresh green beech woodland; (f) fern-dominated forest floor; (g) leaf-littered autumn path; (h) spring herb understorey; (i) bright autumn canopy; (j) flowering spring understorey; (k) small stream in deciduous forest; (l) erosion-prone slope with sparse vegetation.

Mountain ridges, alpine grasslands, steep valleys, waterfalls, springs, rivers, exposed rock formations, erosion-prone slopes and high elevation environments are depicted in Figure 9b. These images are used to support the interpretation of the elevation, slope, moisture, bare-soil and ecosystem degradation analyses.



Figure 9b. Field photographs representing diverse ecosystem conditions in and around Shahdag National Park.

(a) Cloud-covered highland forest; (b) valley and river channel; (c) alluvial plain and settlement zone; (d) waterfall; (e) spring and soil moisture; (f) eroded cliffs and earth pillars; (g) rocky outcrops; (h) eroded slopes; (i) rock formation; (j) alpine lake; (k) snow patches and alpine meadow; (l) snow-capped mountain landscape.

The non-standardized method of photo collection is a qualitative field support to the interpretation of environmental indicators on remotely sensed imagery and identification of potential nature-based restoration priorities. The complete photographic archive supporting Figures 9a and 9b has been published as an open-access dataset to support transparency and reproducibility (Mammadov & Gurbanov, 2026).

Relationship between NDVI and land surface temperature

The correlation coefficients between NDVI and LST were calculated using statistical analysis and showed a moderate anti-correlation ($r = -0.567$). This finding suggests a general negative correlation between LST and vegetation density.

The coefficient of determination was $R^2 = 0.321$, which means that the distinction of the vegetation density accounted for about 32.1% of the spatial variation in land surface temperature.

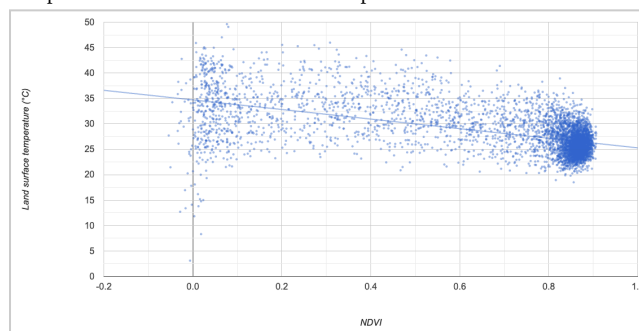


Figure 10. The relationship between NDVI and LST in Shahdag National Park.

From the scatter plot, the general trend shows a decrease in surface temperature as the percentage of vegetation increased, which is

consistent with the scatter plot. The other variation could be linked to such factors as elevation, slope, aspect, soil moisture, solar exposure and surface characteristics.

Forest-cover change

The forest-cover analysis indicated approximately 83,184.15 ha of tree cover in 2000, corresponding to about 63.7% of the total area of Shahdag National Park. During the period from 2001 to 2025, approximately 289 ha of tree-cover loss was detected. This loss amount was about 0.35% of the tree-cover area measured in 2000, suggesting that the level of forest disturbance was relatively small at the park-wide level. The loss detected was, however, not widespread across the national park but rather localized.

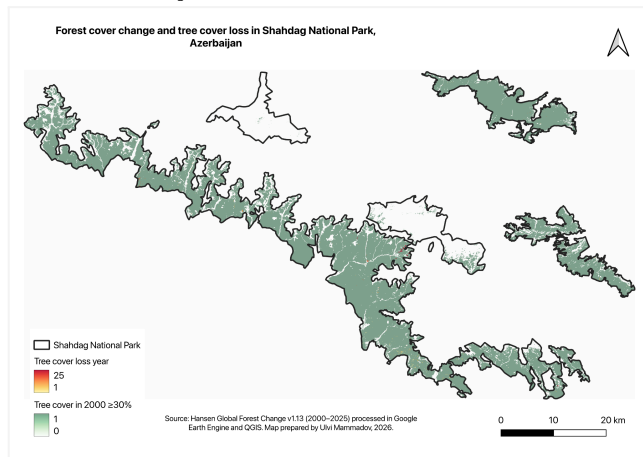


Figure 11. Tree cover in 2000 and detected tree-cover loss in 2001–2025 in The Shahdag National Park.

Detected changes may be a response to fire, wind damage, disease, natural tree mortality, timber removal or other disturbances. The mapped changes should not necessarily be considered as permanent deforestation, as the Hansen data only indicates the presence of tree cover loss and not its cause.

Spatial basis for the financing of restoration.

The results of the raster based assessment revealed that the area analysed in the Shahdag National Park was about 118,182.9 ha. 15,678.7 ha were classified as high relative degradation and 8,571.4 ha as very high relative degradation based on equal interval classification of the EDI values. Both these categories combined account for some 24,250.2 ha or 20.5% of the area analysed in the park. The raster-based assessment covered approximately 118,182.9 ha, representing about 90.6% of the total officially reported area of Shahdag National Park. The difference reflects areas without valid overlapping raster observations or pixels excluded during clipping and data harmonization.

The forest-cover-loss raster revealed around 279.8 ha of forest-cover loss recorded in 2001–25. This area is approximately 0.24% of the park area analysed. Forests-loss zones are directly identified as priorities for field verification as remote-sensing based loss-signal might be anthropogenic disturbance or natural processes.

Table 2. Spatial indicators relevant to restoration financing

Indicator	Estimated value
Analysed raster area	118,182.9 ha
High EDI area	15,678.7 ha
Very high EDI area	8,571.4 ha
Combined high and very high EDI area	24,250.2 ha
Share of priority EDI area	20.5%
Tree-cover loss during 2001–2025	279.8 ha
Tree-cover loss as a share of the analysed area	0.24%

Preliminary restoration financing scenarios

The total EDI area (high + very high) of around 24,250.2 ha was used

to calculate three preliminary financing scenarios. In the low cost scenario (USD 1,000 ha⁻¹), the estimated financing need was around USD 24.25 million. The moderate and intensive-restoration scenarios entailed estimated requirements of USD 48.50 million and USD 72.75 million, respectively, based on USD 2,000 ha⁻¹ and USD 3,000 ha⁻¹. These estimates are indicative values for the scenarios and should not be used as a final restoration budget.

Table 3. Preliminary restoration financing scenarios

Scenario	Assumed unit cost	Estimated total financing
Low-cost restoration	USD 1,000 ha ⁻¹	USD 24.25 million
Moderate restoration	USD 2,000 ha ⁻¹	USD 48.50 million
Intensive restoration	USD 3,000 ha ⁻¹	USD 72.75 million

Note. The estimates are based on the combined high and very high EDI area of 24,250.2 ha. Unit costs are hypothetical analytical assumptions and do not represent verified restoration prices for Shahdag National Park.

Indicative economic benefits of restoration investment

When applied at indicative benefit–cost ratios ranging from 4:1 to 38:1, this yielded a wide spectrum of potential long-term economic, social and ecosystem-service benefits. The gross benefits in the low-cost scenario were estimated to be between about USD 97.00 million and USD 921.51 million. The estimated range for the moderate scenario was USD 194.00 million to USD 1.843 billion. The estimated potential benefits under intensive-restoration scenario were between USD 291.00 million and USD 2.765 billion.

Table 4. Indicative economic benefits of restoration investment

Scenario	Restoration investment	Benefit–cost ratio	Potential gross benefits
Low-cost	USD 24.25 million	4:1–38:1	USD 97.00–921.51 million
Moderate	USD 48.50 million	4:1–38:1	USD 194.00 million–1.843 billion
Intensive	USD 72.75 million	4:1–38:1	USD 291.00 million–2.765 billion

Note. These estimates represent potential gross ecosystem-service and socioeconomic benefits based on an international benefit–cost ratio. They do not represent direct monetary revenue or a site-specific financial forecast for Shahdag National Park.

Spatial patterns of ecosystem condition

The results indicate large spatial variation in the condition of the ecosystems in Shahdag National Park. Lands with higher NDVI and NDMI values were mostly forested and moisture-rich lands, whereas land surface temperature was lower and Ecosystem Degradation Index values were lower. In contrast, exposed and sparsely vegetated areas were more likely to be characterized by low vegetation density, low moisture, high surface temperature and high bare-soil exposure.

However, a low NDVI and a high BSI does not necessarily mean degradation. Similarly rocky and alpine and sparsely vegetated regions, due to elevation, steepness, shallow soil and climatic conditions, may exhibit comparable spectral properties. Hence, a synthesis of NDVI, NDMI, LST, BSI, elevation and slope should be used as a more reliable basis for identification of potential ecological stress (Gao, 1996; Tucker, 1979).

Vegetation and land surface temperature

The result of the analysis showed that there was moderate negative correlation between NDVI and LST ($r = -0.567$). This means the higher the vegetation density, the lower was the surface temperature.

The coefficient of determination was $R^2 = 0.321$, indicating that the spatial variation of the surface temperature was approximately 32.1% explained by the vegetation density. This is in line with the cooling influence of vegetation via shading and evapotranspiration (Weng et al., 2004; Yuan & Bauer, 2007).

The rest of the difference can be attributed to topographic conditions, surface material, exposure to the sun, soil moisture, and slope aspect.

Forest-cover change

An analysis conducted on the forest-cover revealed that there were about 83,184 ha of forest cover in the year 2000 and about 289 ha lost during the period 2001 – 2025. This loss was about 0.35% of the baseline tree cover, meaning that forest disturbance was relatively low across the entire park.

However, localised tree-cover loss can be ecologically significant if it occurs across steep slopes, erosion-sensitive areas or if it contains high values in terms of ecosystem degradation. The Hansen data indicates canopy loss without specifying the cause. Changes detected can thus be related to fire, disease, wind damage, natural mortality or human disturbance (Hansen et al., 2013).

Nature-based solution priorities

The results confirm the application of NbS based on the characteristics of local ecosystems. There may be a need for assisted natural regeneration on forest-loss areas and the restoration of native grass and shrubs, soil stabilization and moisture-conservation measures on exposed and erosion sensitive slopes.

Riparian restoration should be considered for degraded river valleys and, in general, natural rocky alpine areas should be conserved and not artificially afforested. Restoration should thus be tailored to each ecosystem type, and field assessments should be used to support these efforts (Cohen-Shacham et al., 2016; IUCN, 2020).

Table 5. Proposed Nature Based Solution Priorities

Spatial condition	Main ecological risk	Suggested intervention
Localized forest-cover loss	Canopy disturbance and habitat fragmentation	Assisted natural regeneration
Exposed steep slopes	Erosion and runoff	Native grass and shrub restoration
Moisture-stressed vegetation	Reduced ecosystem resilience	Soil-moisture conservation
Degraded river valleys	Bank erosion and habitat decline	Riparian restoration
Stable forest areas	Future disturbance risk	Conservation and monitoring
Naturally rocky alpine zones	Misclassification as degraded land	Protection without afforestation

Note. EDI classes were derived using five equal intervals across the observed raster range. The high and very high categories represent relative spatial priorities and should not automatically be interpreted as areas requiring complete active restoration.

Management implications

Integrated use of remote sensing and GIS can support PA management by determining areas where multiple measures of ecological stress are combined. These results could be used to prioritise field surveys, restoration investments, monitoring activities and sustainable planning for tourism.

The spatial products can also be used for green-finance proposals and environmental decision-making in Azerbaijan. Stable funding, institutional coordination, and monitoring of ecological outcomes will be required for long-term restoration (Mammadov, 2026; Qadimli & Məmmədov, 2026; Sadiqov et al., 2026).

Limitations

There are several limitations in interpreting the results. Satellite based indicators may be affected by seasonality, image-acquisition conditions and spatial resolution. The Ecosystem Degradation Index is not an absolute index of irreversible degradation, but rather a relative screening tool.

The field photographs also give context and are not systematic ground validation. Seasonal imagery should be repeated in future studies,

along with detailed field surveys, slope aspect, precipitation, fire history, and grazing intensity and tourism pressure.

Financial and green finance implications

The high and very high relative degradation identified (approximately 24,250.2 ha) serves as an initial spatial basis for estimating the financing needs for restoration. But not the entire priority area should be considered as needing the same intervention. An active revegetation or erosion-control regimes may be needed at some sites, while assisted natural regeneration, protection from disturbance or long-term monitoring may be appropriate at others. Thus, field verification is required prior to assigning the unit restoration costs.

The economic benefit of spatial prioritisation is its ability to focus scarce resources on the most ecologically vulnerable places. Rather than spending the same amount of money throughout the park, restoration funding can be targeted by degradation intensity, forest-cover loss, slope, and vegetation moisture and accessibility. The strategy could help to avoid wasteful spending and to make public environmental investments more cost-effective.

The scenario analysis suggests that nearly USD 24.25–72.75 million is needed to restore the whole high and very high EDI area, depending on selected intensity of the interventions. This band width, however, likely exceeds the amount of investment necessary for active restoration as not every priority pixel would need to be planted, and engineering activities and intensive rehabilitation would not be necessary. Protection and/or assisted natural regeneration or periodic monitoring may be all that is needed in some areas. This moderate scenario, of roughly USD 48.50 million, should thus not be interpreted as a concrete investment figure, but rather as a provisional planning figure.

A staged funding plan is more likely to be feasible than funding the whole priority area at once. Potential priority areas for the initial funding include field verification, forest-loss sites and erosion-prone slopes and areas where multiple indicators of degradation are present. The future investments could then be made according to the intervention-specific unit cost, ecological effectiveness and monitoring results. Environmental cost–benefit analysis can help to compare these costs with the long-term benefits of ecosystem services (OECD, 2018). Benefits of potential restoration include avoidance of soil erosion, enhanced water control, carbon capture, and the maintenance of habitats and landscapes for tourism and recreation. Environmental cost–benefit analysis offers a tool for assessing and balancing these benefits against the costs of project implementation and maintenance over the life of the project (OECD, 2018). International evidence also suggests that the nature restoration can create around EUR 4-38 in economic value for every EUR 1 spent (European Commission, n.d.) (not as a direct estimate for Shahdag National Park, but as an international benchmark).

The scenario results indicate that restoration of these ecosystems can yield benefits that could significantly outweigh the costs of restoration. For the moderate scenario, the indicative gross benefits were estimated at USD 194.00 million to USD 1.843 billion with an estimated investment of around USD 48.50 million. The values are not intended as cash incomes. Rather, they reflect the highest value of ecosystem services such as carbon sequestration, erosion control, water regulation, biodiversity conservation, recreation and avoided environmental damage. Since the benefit cost ratio applied was based on research done abroad, the economic return would need to be calculated using an ecosystem-services approach and a discounted cash-flow approach to determine the benefits and costs at the national-park level.

Public environmental expenditure, green bonds, concessional finance, international biodiversity funds, environmental grants and public-private partnership can be used to support restoration activities. The maps generated by this study can be used for project preparation to delineate zones of intervention, estimate the size of those zones and give indicators for future monitoring of ecology. This is relevant as investment in NbS at the global level is still not at the level needed to achieve the goals of biodiversity, climate, and land-restoration (United Nations Environment Programme [UNEP], 2026).

CONCLUSIONS

The results of this study illustrate how the combination of remote sensing, GIS, forest change analysis and field photographic observations can be used to evaluate the condition of an ecosystem and the priorities for NbS in Shahdag National Park in Azerbaijan. Results from the combined analysis of NDVI, NDMI, LST, BSI, Elevation, Slope and Forest-cover change showed that there was significant spatial variation in the ecosystem condition over the study area. Moderately low negative correlation between VD and LST indicated the significant role of vegetation in regulating the LST.

The results show that the majority of the forest areas in the park are in relatively stable conditions but there are localised areas where forest ecosystems are degraded, soil is bare, soils are subject to erosion and areas of tree-cover loss warrant ongoing monitoring and targeted restoration. From this, assisted natural regeneration, erosion-control measures, riparian restoration and soil-moisture conservation are recommended as suitable NbS for different landscape conditions.

In addition to its use for planning in Shahdag National Park, the presented framework provides an example of how to implement a system for evidence-based conservation planning in other protected mountain areas using freely available data from satellite imaging, GIS and field observations. The public availability of the spatial data and photographic archive created in this study also helps to increase research transparency, the ability to replicate work and for future ecological monitoring. The study, in general, offers basic practical data for managers of protected areas, sustainable tourism planning, conservation of biodiversity and green development in Azerbaijan.

The spatial prioritization approach can help to maximize the impact of restoration investments by focusing public fund and green-finance on the areas with the highest ecological value. The findings can help to prepare restoration budgets, environmental grants, green bonds and climate-finance proposals. Over the longer term, ecosystem restoration investments could yield economic returns from avoided degradation, water regulation, erosion risk reduction, biodiversity conservation and the sustainable tourism potential. International evidence indicates that such benefits can be well in excess of the cost of restoration, though the benefits can vary depending on the type of ecosystem and the value and method of intervention (European Commission, n.d.; OECD, 2018).

From a financial perspective, the study identified approximately 24,250.2 ha as having high or very high relative degradation and approximately 279.8 ha of recorded tree-cover loss during 2001-2025. These spatial indicators provide an initial basis for estimating restoration budgets and prioritizing green-finance resources. The proposed framework may support the preparation of environmental grants, public restoration programmes and other nature-finance projects by linking investment decisions with measurable ecological conditions. Nevertheless, field verification and locally appropriate unit-cost data are required before determining the final restoration budget. The combined priority area has a preliminary financing

requirement of between approximately USD 24.25 million and USD 72.75 million, depending on the three indicative unit-cost scenarios, with a moderate planning scenario of approximately USD 48.50 million.

The benefit-cost ratio for the international scale ranges from 4:1 to 38:1, which suggests that the moderate restoration scenario may be able to generate long-term gross ecosystem service and socio-economic benefits of USD 194.00 million to USD 1.843 billion. These values are indicative and should not be viewed as a direct financial revenue or a site specific forecast.

AUTHOR CONTRIBUTIONS

Conceptualization, N.Q. and U.M.; methodology, N.Q. and U.M.; remote sensing and GIS analysis, U.M.; data processing and visualization, U.M.; investigation, N.Q. and U.M.; ecological and financial interpretation, N.Q. and U.M.; writing—original draft preparation, U.M.; writing—review and editing, N.Q. and U.M.; supervision, N.Q. All authors have read and agreed to the final version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

FUNDING

This research received no external funding.

DATA AVAILABILITY

The datasets and geospatial outputs supporting the findings of this study are publicly available through ResearchGate. The remote sensing-derived maps of ecosystem condition and degradation in Shahdag National Park are available at DOI: 10.13140/RG.2.2.36843.30243. The field photographic dataset documenting forest ecosystems, mountain landscapes and ecological features in and around Shahdag National Park is available at DOI: 10.13140/RG.2.2.19542.41280. Additional satellite and geospatial data used in the analysis were obtained from publicly accessible Earth observation datasets described in the Materials and Methods section.

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Evaluating municipal governance in the context of socioeconomic development in the Central Aran region

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Keywords

Decentralization, local governance, municipal finance, regional development, socioeconomic indicators

ABSTRACT

In the Central Aran region of Azerbaijan, this research examines the linkage between the capacity of municipal governance and the patterns of socioeconomic development. The analysis is a mix of official socioeconomic data for Mingachevir city and the Agdash, Goychay, Kurdamir, Ujar, Yevlakh and Zardab districts, with municipal administrative and fiscal data, national oversight data and an international benchmark. Harmonised data on governance at municipality level are not consistently available for all territorial units, so it is not possible to apply causal estimation, but instead, a descriptive comparison and institutional triangulation approach are applied. According to the official data of 2025, there were 73.6 thousand paid employees in Central Aran with a performance payment of AZN 681.8 per month on average (nominal wage), 21,155 people were registered as unemployed, and jobs in the region increased by 693 during the first 9 months of the current year. The annual revenues of the Mingachevir municipal case were AZN 465,000.61 and the expenditures were AZN 385,703.85 where land rent and municipal property sales were the biggest revenue sources and employee compensation, the biggest expenditures. There are also indications that administrative supervision has been strengthened and the reporting system is being digitized at the national level. The need for more own-source revenues, strategic budgeting, evidence-based planning and participatory governance by comparison with Poland. The results indicate that fiscal capacity, citizen interaction, and scale down improvement projects and institutional coordination are the major elements that are linked to local development through municipal governance although it has a limited measurable impact due to the limited availability of standardized local fiscal and performance information.

INTRODUCTION

Municipal governance is one of the institutional pathways where local public priorities, land management and small-scale infrastructure, social support and citizen participation contribute to territorial development outcomes. This relationship quality is not only based on whether or not local governments exist, but also on whether or not these local governments' responsibility is clearly defined, whether their own-source revenues are sufficient, and their level of accountability and ability to coordinate with higher levels of local governments. Thus, comparative research views decentralization as an institutional arrangement whose impact on development depends on certain conditions (Faguet, 2014; Smoke, 2015). The OECD also stresses that the articulation of expenditure responsibilities, own revenues and intergovernmental transfers is vital to a well-functioning subnational government (OECD, 2020).

The theme is especially well to the Azerbaijan, as the municipalities function side-by-side a high level of state administrative capabilities and municipalities fiscal and functional capabilities have long been discussed with reference to the European Charter of Local Self-Government. The Congress of Local and Regional Authorities of the Council of Europe has noted progress in terms of transparency and practice and that despite the same time structural challenges to municipal self-government have been identified as the lack of own funds, the lack of powers, and dependence on the state (Council of Europe, 2021). The local crisis also originates from recent national

reforms, such as the merger of municipalities and greater digitalisation of reporting, which could lead to a reevaluation of the role of municipalities in local socioeconomic development.

The Central Aran Economic Region is suitable for such an assessment, during which the complex of such districts can be combined with an important urban center, such as Mingachevir. The economic region includes Mingachevir city and Agdash, Goychay, Kurdamir, Ujar, Yevlakh and Zardab districts (SSC, 2025a). These territorial differences indicate that, the conditions of local development under which municipalities operate are not the same everywhere. Municipal governance should therefore not be considered as a detached administrative variable, but as one of a range of socioeconomic variables in each of the territories.

More recent studies of the Azeri researchers also reveal the importance of considering economic, environmental and spatial indicators when assessing regional development. Arifzade et al. (2026) utilized economic and ecological evidence to determine urban pollution pressures and Sadiqov et al. (2026) studied the investment in renewable energy with the supplementation of financial instruments. Additionally, environmental variability has been linked to economic exposure through the use of satellite and geospatial methods (Qadimli et al., 2026), while the surface heat patterns and vegetation patterns have been interpreted in a comparative city context at a qualitative level (Qadimli & Mammadov, 2026). While not directly focusing on municipalities, these studies demonstrate the general shift in a way of

analysis in the direction of evidence-based multi-indicator approach in assessing territorial sustainability in Azerbaijan and beyond.

Therefore, the objective of the current study is to examine how municipal governance is related to socioeconomic development indicators in the Central Aran area. The study seeks to investigate the interplay between the socioeconomic characteristics of the region and the conditions in the municipality in terms of financial capacities, institutional oversight and citizens' involvement in administration. Given the lack of comparable municipality-level governance indicators that are available in a harmonised format for all territorial units, no attempt has been made to estimate a causal effect. To do so, it utilises descriptive comparison and institutional triangulation, leveraging the case of Mingachevir Municipality as a detailed local case and relying on and examining these national municipal governance indicators. Through this design, the process of analysis identified possible governance-development connections, and exposed the nature of the available data, including its weaknesses.

LITERATURE REVIEW

Decentralisation is more or less connected with the debate about local governance and development from a theoretical perspective. One key claim is that decision-making should be decentralized to the citizens to enhance information flows, as well as responsiveness and accountability, given local authorities' greater ability to know citizens' desires at the local level. However, as Faguet (2014) demonstrates, decentralization is not inherently a desirable reform; the design of institutions and the characteristics of political incentives and the allocation of fiscal authority all influence whether local government will make it more (or less) effective and adaptive. Similarly, Smoke (2015) argues that there are limits to how well decentralization reforms can perform, as responsibility, capacity and resources are misaligned. Such arguments have obvious relevance for municipal development analysis in Azerbaijan where fiscal space and differentiation of responsibilities give municipalities a certain spectrum of possibilities to focus on.

Especially important is fiscal capacity. Even when cities have legal obligations, they may also lack resources for introducing development-oriented programmes due to narrow revenues, which are unpredictable, or transfer-dependent. The OECD (2020) thus makes a distinction between expenditure decentralization and revenue decentralization and puts a significant emphasis on the importance of own-source revenues for local accountability. Clear linkages between where county and municipal revenues come from and where services are provided can increase the incentive for providing good performance by county and municipalities, as well as for citizen oversight. On the other hand, when responsibilities and ability in revenue generation do not fit together, it may enable short-term administrative expenditures instead of strategic investments.

This is reflected in the institutional context in Azerbaijan. Municipalities' own financial resources and lack of exclusive and full powers remain as constraints according to the Council of Europe (2021) which noted that some progress has been achieved in municipalities with regard to transparency and a few aspects of practice. A municipality in a relatively dynamic local economy could have few direct tools for influencing employment, investment or wage outcomes if the relevant policy tools are highly localized but operates at other level(s) of government. Thus, it is necessary to measure municipal governance by means of norms where the possibility of local influence is greatest, namely in local land and property administration, neighborhood improvement, local social support,

citizens' contact with the administration, and local project cooperation.

Empirical studies conducted recently in Azerbaijan suggest applying multidimensional evidences in regional policy studies. Instead of only looking at individual indicators, Arifzade et al. (2026) found value in analysis of interaction between particulate pollution indicators and industrial and transport parameters. Sadiqov et al. (2026) demonstrated that investing and financial structures have a significant role in converting sustainability goals into concrete development outcomes. An economic exposure metric was used alongside satellite observations to gauge water-related risks, highlighting the value of integrating physical and socioeconomic data (Qadimli et al., 2026). Qadimli, Mammadov (2026) also used urban growth and vegetation & surface temperature indices for analyzing the spatially variable development patterns. Collectively the studies confirm the methodological rationale behind linking governance evidence to resulting socioeconomic conditions, instead of simply bringing governance to the purely legal and descriptive realm.

It's helpful to have some international benchmarking, too. Poland is relevant, because this post-1989 reform package of political and fiscal decentralization and a multi-tier system of local autonomy governs the country. According to OECD (2021), strategic planning, management based on evidence, budgeting, open government and workforce capability and inter-level coordination are among the most important aspects in the exercise of effective local self-governance in Poland. The report further emphasizes the importance of the rationalization of the responsibility-spending matrix, and an improvement of public investment quality for local development results. The World Bank, fiscal equalization in Poland analysis also highlights that the effectiveness of intergovernmental transfers in delivering equitable public services between territories with different revenue and expenditure levels is shaped by the design of intergovernmental transfers. The Polish experience is not directly transferable to Azerbaijan; however, the general principles of the model are useful to compare with the level of fiscal autonomy, planning and accountability in Azerbaijani Central Aran.

Thus, literature implies a conceptual process where there is an indirect relationship between municipal governance on one hand and development on the other. The size of policy space for local action is dependent upon fiscal capacity, and the quality of administration is a factor in how decisions are made, administered, and how close they are to being legal; citizen involvement helps build information about what local needs are, and coordination with other state institutions determines whether or not local action can at least complement larger state infrastructure and development projects. The four-part framework – fiscal capacity, administrative activity, citizen engagement and institutional coordination – is adopted in the present study as a means of interpreting the evidence that is available from Central Aran.

MATERIALS AND METHODS

Study area

The study is conducted in the Central Aran Economic region of Azerbaijan which includes such districts as Mingachevir city, Agdash, Goychay, Kurdamir, Ujar, Yevlakh, Zardab. As to the geographical position the region is in the central lowland zone of the country, it's organization is based on the Kura river system, the corridors of transport, the agricultural production centres as well as the urban-industrial function of Mingachevir. Figure 1 shows the administrative and principal hydrographic features of the area considered as the study area.

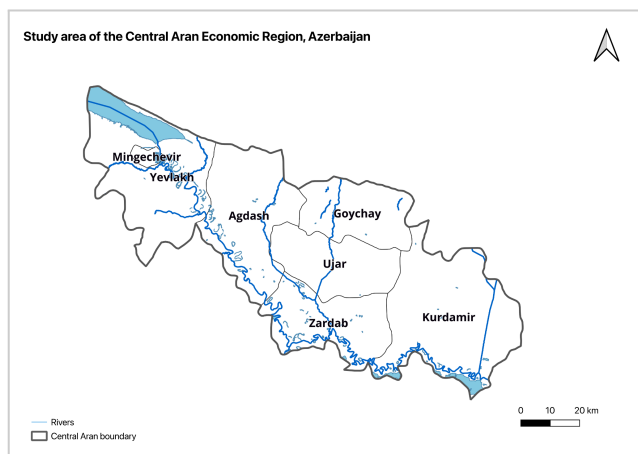


Figure 1. Study area and administrative structure of the Central Aran Economic Region, Azerbaijan.

Data sources and variables

The socioeconomic component is first of all based on the official information published by the State Statistical Committee of the Republic of Azerbaijan. The data of paid employment, average monthly nominal wage, registered unemployment and the number of newly created jobs for 2025 in the seven territorial units were identified from socioeconomic statistical materials for 2025. The SSC municipal finance portal and the 2025 municipal budget execution bulletin were used to determine the general municipal reporting mechanism, as well as the presence of municipal revenue and expenditure statistics (SSC, 2026).

Municipal governance evidence was taken from two complementary sources. The activity report of Mingachevir Municipality for 2025 also contains detailed administrative and financial data, such as the number of meetings, agenda points, applications from citizens, financial resources according to their origin and output expenses according to the category from which they are paid (Mingachevir Municipality, 2026). Secondly, data from the MoJ (National) was used for the description of the legal environment of oversight, methodological support, and digitalisation which all the municipalities face. In 2025, the Ministry reported legal examination of 81,711 municipal acts, appeals reviewed – 4132, extensive recommendations and awareness activities in this field (Ministry of Justice of the Republic of Azerbaijan, 2026a). According to a separate digitalization update, in 2025, all municipalities in the country had connected to the internet and thus it became possible to submit municipal acts electronically via the information system "Bələdiyyələrə iş" (Ministry of Justice of the Republic of Azerbaijan, 2026b).

Analytical approach

This study has an explorative mixed-source design. Intraregional socioeconomic variation is identified in the first place by means of descriptive comparison. Second, the Mingachevir case is studied as a Fiscal and Administrative Governance anchor, as a report of the city's report of their expenditures is publicly accessible and includes detailed information about items for 2025. The shares in the revenues and expenditure were determined from monetary values reported. Third, the formal/virtual dimension of national oversight and digitalisation is seen as institutional determinants of local accountability and capacity. Finally, the patterns observed are contrasted with governance principles implied by the Polish experience as captured by the OECD (2021) and the World Bank (2014) reports.

The analytical notion of 'relationship' is necessarily non-causal. At the time of the study there was a lack of a comparable open-data harmonized panel with governance indicators at the municipality level in all Central Aran districts and socioeconomic outcomes. It would thus be unwarranted to estimate any causal coefficient, or directly link with municipalities wages, employment or job creation. Rather, the study analyzes whether the size and makeup of the municipal resource, decision making activity, and citizen involvement are institutionally appropriate for the socioeconomic needs and patterns of socio-economic development found in the region. This is also according to the template requirement to separate evidence that is directly evidenced by the analysis from general interpretation.

Monetary amounts are in Azerbaijani manat (AZN). The component shares of Mingachevir was determined by the ratio of each of the components to total municipal revenue/total expenditure, expressed as a percentage. Absolutely no personal data were collected and the study is solely based on statistical, administrative and academic sources which are publicly available.

RESULTS AND DISCUSSION

Socioeconomic profile of Central Aran

There is significant variation in the 2025 indicators in the region of Central Aran. According to the data, there were 73.6 thousand people who were registered as employed, the average nominal wage per month was AZN 681.8, while there were 21,155 registered unemployed people and 693 new jobs were created in the first nine months of 2025 at the regional level (SSC, 2025b). Among the units in the list, the highest number was paid employment of Mingachevir (16.6 thousand), while the average salary for a paid employee was the most in Mingachevir (AZN 720.5). Kurdamir (9.6thousand paid employees) had the highest number of new jobs in the region in that period (315 new jobs in January-September 2025). The average wage of Goychay was considered as the lowest one and it registered the highest unemployment figure among the 7 units with 5147 people.

Table 1. Central Aran Economic Region: selected socio-economic indicators 2025

Unit	Paid employees (000s)	Avg. wage (AZN)	Registered unemployed	New jobs Jan-Sep
Central Aran total	73.6	681.8	21,155	693
Mingachevir	16.6	720.5	2,581	171
Agdash	7.8	676.1	2,788	39
Goychay	11.5	656.1	5,147	64
Kurdamir	9.6	718.4	3,247	315
Ujar	7.8	676.1	2,234	14
Yevlakh	12.6	679.4	2,794	51
Zardab	5.4	671.6	2,364	39

Source: SSC (2025b). Period definitions follow the official report; new jobs refer to January-September 2025.

These indicate the need to use a regional average figure – is too low – for a local governance analysis. Gini coefficient difference between the highest and lowest reported average wage is AZN 64.4 in current period with high level of job-creation being concentrated in Kurdamir and Mingachevir. This difference is likely to mirror differences in industrial structure, agriculture and variations in state and private investment, transport accessibility and enterprise dynamics, and local institutional conditions. Municipalities shouldn't, therefore, be read as the only factor behind the results reported on Table 1. What they

can more realistically achieve is to influence the local enabling environment by the administration and control of land, the provision of neighbourhood facilities, and through small-scale projects that can respond to the wider economic forces with which they interact.

Financial and administrative capacity of municipalities: The case of Mingachevir.

The municipal evidence on which this study is based is most comprehensive for Mingachevir. During the year 2025, there were 32 meetings and 208 agenda items of the Municipality. It has been receiving 1183 applications and letters, as well as 237 citizens directly (Mingachevir Municipality, 2026). These numbers point toward a significant burden of administration and of relations between citizens and administration, and they enable to look at governance not only as a set of legal relationships, but also as a functioning local interface.

The total revenue of the municipality was reported to be AZN 465,000.61, which is 13 per cent higher than in the previous year, and total expenditure amounted to AZN 385,703.85. Summing these items up arithmetically gave about AZN 79296.76. The revenue from Land rent was AZN 160,064.36, which accounts for 34.4% of the revenue, while the sale of municipal property revenue stood at AZN 115,255 or 24.8%. Total revenue was AZN 465,000, of which 17.4% was through the state subsidy (AZN 81,000). In terms of expenditure, the total of salaries and wage-related additions and other deductions from payroll stood at around AZN 312,410.29, representing 81.0% of all expenditure. Of the total, approximately 4.8% was allocated for improvement and construction expenditure and 3.9% for material assistance. The governance and finance indicators are summarized in table 2.

Table 2. Strength of municipal governance and fiscal performance (selected indicators), in Mingachevir, 2025

Indicator	Value	Interpretation
Municipal meetings	32	Administrative activity
Agenda issues	208	Decision-making workload
Applications and letters	1,183	Citizen/service interaction
Citizens received by chair	237	Direct engagement
Total revenue	AZN 465,000.61	+13% year-on-year
Land rent	AZN 160,064.36	34.4% of revenue
Municipal property sales	AZN 115,255.00	24.8% of revenue
State subsidy	AZN 81,000.00	17.4% of revenue
Total expenditure	AZN 385,703.85	Annual spending
Employee compensation*	AZN 312,410.29	81.0% of expenditure
Improvement/construction	AZN 18,586.62	4.8% of expenditure
Material assistance	AZN 15,022.49	3.9% of expenditure
Arithmetic budget balance	AZN +79,296.76	17.1% of revenue

Source: Mingachevir Municipality (2026); author calculations. *Salary, wage-related additions and other payroll deductions.

It is analytically important what kind of actual budget the budget is. Strong linkages to local property and land management can be observed in the prominence of land rent and asset sales by contrast with the relatively little amount going directly to improvement and construction, which indicates limited scope for large-scale development intervention. Meanwhile, the annual positive balance and revenue increase of 13% suggest some financial stability. So, the overall impression given by the case is a combination of active local revenue sources, extensive administrative contact, but still personnel

expenses taking up an absolute majority of the municipality's expenditures. This is in line with the concern of the Council of Europe on limited financial capacities of Azerbaijani municipalities in comparison to their development expectations (Council of Europe, 2021).

The connection with socioeconomic development should therefore be interpreted in the margins and values of accommodation and empowerment, and as opposed to macroeconomic control. The sizable employment base and relatively high average wage of the municipality of Mingachevir can be explained not only by the municipality itself but the industrial and service structure of the city is fundamental. In addition, municipal Land Use allows, and potential business and property applications and neighborhood improvement and response to residents in need, to have an impact on the quality of the local economic environment. The findings are consistent with the broader sustainability literature in Azerbaijan, which reveals that translation of the development goals into outcomes is not direct, but proceeds through financial and institutional mechanisms (Sadiqov et al., 2026).

Administrative management, legalization and digitalization

The national overview context also influences municipal governance capacity. In 2025, the Ministry of Justice announced that a total of 4,132 appeals linked to municipal activity and 81,711 municipal acts were subject to legal examination. 1,647 acts were amended or repealed after the oversight interventions while 6,074 recommendations were sent to municipalities. There have also been 273 awareness-building and methodological events with over 7 thousand representatives of municipalities (Ministry of Justice of the Republic of Azerbaijan, 2026a). These indicators, reported on the Web, are summarized in Figure 2.



Figure 2. Administrative supervision and methodological support indicators for municipalities in Azerbaijan, 2025.

Source: Ministry of Justice of the Republic of Azerbaijan (2026a). Web-source indicators adapted by the author.

Such indicators suggest that the municipal governance is tightly integrated with a thick legality and capacity building regime. Oversight can take two forms as relates to development. First, it can alleviate legal uncertainty and enhance the quality of land, property and administration decisions, thus playing a role in local investments and trust of citizens. Second, too compliance-focused a model may leave too little time or energy for strategic development with limited municipal resources to devote to the process. Hence, supervision is not the policy goal but they are allied with greater planning, budgeting and service-delivering capacity.

Digitalization is a connected institutional change. According to the Ministry of Justice, in 2025, the Ministry of Justice for the first time provided all Bələdiyyələr [municipalities] in Azerbaijan with access to the internet, and provided technical support for the electronic publication of Bələdiyyələr acts via the information system "Bələdiyyələrə iş" [With municipality on-line] which opens the road

of more systematic on-line work with the Bələdiyyələr (Ministry of Justice of the Republic of Azerbaijan, 2026b). Digital reporting will reduce administration transaction costs and facilitate collection of comparable performance information in the future. This is an opportunity for Central Aran to shift their reporting from one-off reports to a common, replicable municipal data architecture, which in the future could help them to perform comprehensive panel analysis on governance and development results.

Citizen participation and linkage to local services

Mingachevir Municipality's web presence demonstrates the advantage of using a digital tool to combine with in-person communication. It has a citizen application option (Bələdiyyəyə #SözümVar) on its website, and according to its activity report, in 2025, there were a considerable number of applications and their direct receipt. This local digital engagement channel is visualised in Figure 3, along with any important interaction indicators for 2025 (Mingachevir Municipality, 2026).

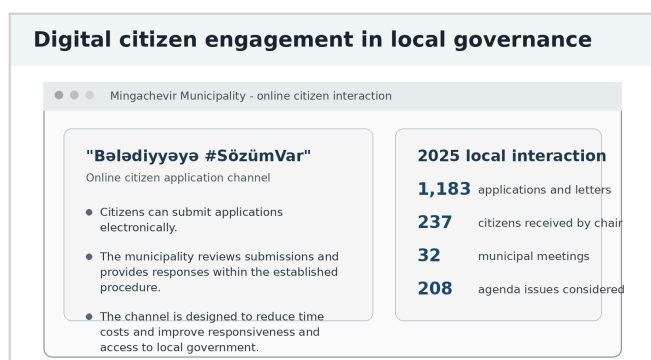


Figure 3. Digital citizen engagement channel and local interaction indicators in Mingachevir.

Source: Mingachevir Municipality website and 2025 activity report (2026).

Web-source content adapted by the author.

There is a relationship between citizen engagement and socioeconomic development since much of the issues that municipalities are often deciding on are very local and perceptible only in aggregate data. The information provided to the municipalities in applications concerning land, business, construction, trees, certificates and social assistance, gives a guide as to immediate needs and bottlenecks. Such information, if coupled with clear budgeting and service targets that can be measured, can enhance prioritization. The major hurdle is to take a large number of requests and make it systematic, evidential documentation for planning – rather than processing individual applications as single administrative instances.

International benchmark: lessons from Poland

The Polish experience can be a helpful comparative backdrop for this transition. Poland has more decentralized and institutionally distinct form of local self-government than Azerbaijan and the OECD evaluation also outlines a number of principles that can be translated into practices. These cover evidence-based strategic planning, coordination with other administrative units and policy areas, better multi-level governance, investment planning, medium-term and performance-based budgeting as well as strategic human resources management, and open government (OECD, 2021). The report also highlights the need for match between responsibility and financial capacity, which is a direct concern in Azerbaijan's context related to the fiscal constraints noted.

An additional important lesson is fiscal equalization. According to World Bank analysis in Poland, intergovernmental revenue-sharing and equalisation arrangements have an impact on the ability to

provide reasonably comparable public services to residents in different localities despite interlocalities differences in local tax bases (World Bank, 2014). With respect to central Aran, which exhibits strong intergovernmental employment differences (see Table 1), a similar principle would be to introduce predictable intergovernmental support without undermining the incentives to mobilise own sources of revenue. The transfers should take account of the revenue-generating capacity and expenditure requirements at the local level and promote efficiency in local revenue collection and management of local resources.

There are three implications as a result. Firstly standardized medium-term budgets, for municipalities, that distinguish between administration costs and service outputs and between development output and administrative/non-development costs, must be prepared. Secondly, the participatory systems must be linked to the published priorities and measurable project outcomes such that citizens influence resource allocation. Third, intermunicipal and state-municipal coordination optimisations should be encouraged for functions with an economic scale that goes beyond one municipality, such as waste management, tourism development, transport-related land use and environmental improvement. These principles align with a green-economy understanding through which the dimensions of the general public finance and public administration of regions and communities could help build sustainable infrastructures and sustainable use of resources (Sadiqov et al., 2026).

Understanding the governance-development relationship

Overall, the evidence points to an otherwise positive, albeit limited, correlation between governance and development. The City of Central Aran has unique local avenues—land administration, neighborhood improvement, social assistance, and citizen communication and coordination with public institutions—to influence development. These channels are active, as exemplified by Mingachevir, but they also illustrate why assessing the effect of a municipality on indicators is challenging. The city economy is large compared with its municipal budget, which is largely allocated towards wages for public sector employees and the overall situation in the labor market relies on the activities of the enterprises, national investments, sectoral structure and state policies.

This is in line also with the general empirical rationale of modern Azerbaijani research. Financial mechanisms could either facilitate or hinder sustainable investments (Sadiqov et al., 2026); economic and environmental results are the result of interacting pressures (Arifzade et al., 2026); and spatial and socioeconomic information should be combined to understand territorial exposure (Qadimli et al., 2026; Qadimli & Mammadov, 2026). Properly the governance of municipalities should also be regarded as one part of a multi-level regional development system. It can be more quantifiable when it has a local fiscal information base that shows on a consistent territorial and temporal basis the service products and socio-economic indicators.

This study thus uncovered the greatest weakness in the policies as a data gap. There are comprehensive regional socio-economic data held by the State Statistical Committee and the launching of a municipal budget reporting system by the State Statistical Committee (SSC 2025a, 2026) and valuable administrative information by municipalities and the Ministry of Justice. Associations between revenues from own sources, transfers, functional expenditures, service outputs, citizen-engagement and local socioeconomic outcomes, which would be standard to researchers, are not easily available in a harmonised open format at this point and are, in part, not yet available

over multiple years at each individual municipality level. Development of such a dataset would be sufficient to move the studies from descriptive triangulations to panel regressions and spatial analysis and quasi-experimental evaluation without having to make unsupported causal claims.

CONCLUSIONS

The authors of this study used official socioeconomic statistics, detailed municipal case, national oversight and digitalization evidence and an international benchmark to measure the relation between the municipal governance and socioeconomic development indicators in Central Aran region. The outcome indicates that considerable distinctions can be found across the intraregions with respect to employment, wages, registered unemployment and new job creation. In terms of size of paid employment base, Mingachevir led the seven territorial units, and Kurdamir reported the highest average monthly paid wage, while the largest number of newly-hired workers was also observed in Kurdamir in the first nine months of 2025. Such differences indicate differences between regions in Central Aran in terms of socioeconomic standing and local governance has to be understood against the backdrop of the territorial variability.

The lessons learnt from the example of Mingachevir are that it is applicable but not comprehensive. The municipality had ongoing decision making processes and citizen engagement and it was able to raise revenue through land rent, property transfers, taxes and fees, and a state subsidy. Meanwhile, reported spending was for about four-fifths of employees' compensation, and direct improvement and construction spending was relatively small. The expenditure pattern indicates the highest scope for a credible role of the municipality in socioeconomic development policies as a local enabling function and in projects.

These channels can be reinforced with the help of national reforms. The use of electronic forms for issuing municipal acts, the use of larger information on digitalization, as well as legal supervision and methodological assistance can facilitate the traceability and the accountability and improve the quality of administrative acts. However, more compliance should go hand in hand with greater fiscal capacity and development management. Polish benchmark shows that there are certain principles that are particularly important for better local development governance: evidence-based strategic planning, medium-term and performance budgeting, predictable fiscal equalisation, open government and multi-level coordination.

The main drawback of the study is the lack of a combined municipality level-panel with governance, finance and socioeconomic information for all Central Aran municipalities. Thus the results be seen as an exploratory determination of associational and institutional mechanisms and not as a causal estimation. Moving forward, multi-year municipal datasets should be developed, and transfers separated from own source revenues, expenditure categorized by service function, and the indicators correlated with indicators of local employment and enterprises, infrastructure and environmental outcomes. Such a framework will allow conducting more profound statistical and spatial assessments of influence of municipal capacity on balanced and sustainable regional development in Azerbaijan.

AUTHOR CONTRIBUTIONS

Conceptualization, N.A.; methodology, N.A.; formal analysis, N.A.; investigation, N.A.; data curation, N.A.; writing-original draft, N.A.; writing-review and editing, N.A.; visualization, N.A. The author has read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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DATA AVAILABILITY

All quantitative data used in this study are derived from publicly accessible sources cited in the manuscript, including the State Statistical Committee of the Republic of Azerbaijan, the Ministry of Justice of the Republic of Azerbaijan and Mingachevir Municipality. Derived percentage calculations are reported in the text and tables. The study-area map was prepared in QGIS from administrative boundary and hydrographic spatial data.

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Urbanization built-up density and land surface temperature patterns in central Baku Azerbaijan

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Keywords

Built-up density; Google Earth Engine; land surface temperature; remote sensing; urban heat.

ABSTRACT

Pollution and urban development with a high building density, paving and transport networks can alter the energy balance on urban surfaces, or increase thermal stress. The spatial correlation between urbanization, built-up density and summer Land Surface Temperature (LST) is assessed in the study area that is 88.40 km² central Baku delineated manually. In Google Earth Engine, Landsat 8 and 9 Collection 2 Level 2 data from June - August 2024 was processed to generate a summer surface LST after performing cloud and water masking. Built-up density was calculated based on the built-up surface from the 2020 Global Human Settlement Layer and was reported as the percentage coverage of built-up surface in areas covered by the grid cells of 100 x 100m and was expressed as a percentage. Urban heat hotspots (UHH) were defined as heat hotspots with high LST temperatures (≥ 45 °C) and high built-up density ($\geq 70\%$). The mapped LST varied between LST~30.73 °C and LST~52.60 °C and the built-up density varied between 0 and 98.04%. Combined with industrial, transport-oriented, large-roof areas, and densely developed areas, the joint hotspots were most strongly expressed in three representative zones that were identified as the central coastal hotspot (Zone A), the eastern urban hotspot (Zone B) and the northern urban hotspot (Zone C). Results reveal a clear sense of spatial association between high built density and high surface temperatures, and that surface temperature is influenced by land-use characteristics at the local level and the urban morphology. The results of this study illustrate the usefulness of the synergy between Landsat and GHSL data for fine-scale screening of urban heat for the city of Baku, for planning and adaptation to heat stress, and for urban greening and climate-resilient investments.

INTRODUCTION

The urbanisation process alters thermal behaviour of land surfaces, through the conversion of vegetated and permeable surfaces to roofs, roads, parking areas and other impervious surface materials. The high number of these surfaces are typically associated with expressing large sensible heat storage, an effect of evaporative cooling and a shift in aerodynamic exchange resulting in strong spatial variations in urban surface temperature. Both radiation balance modification and heat storage and turbulent flux modification have been long associated with urban areas and the resulting physical basis of the UHI (Oke, 1982). Later, these contrasts were mapped at the city scale with the help of satellite thermal observations, and the use of the thermal remote sensing approach is now well established to assess the intra-urban heat pattern and how this is linked to structure of land cover (Voogt & Oke, 2003; Zhou et al., 2019).

Although the temperature at the land surface is not equal to the near surface air temperature, LST is a valuable measure of the thermal state of roofs, bare ground, pavements and urban vegetation. At the neighbourhood scale, LST has a great potential use, as the spatial footprint of the thermal infrared radiation reflects the spatial structure of land-cover mixture and surface properties. Previous efforts using Landsat data showed a high correlation between LST and vegetation

volume (Taubenkoig et al., 2002), and subsequent studies applied this methodology to impervious surface (Weng et al., 2004), urban density and urban landscape pattern (Fu & Weng, 2016; Estoque et al., 2017). The relationships are significant to cities where the development (construction and transport) and natural (evapotranspirative surfaces) components of the urban environment are heavily concentrated and where evapotranspirative surfaces are limited during warm seasons.

Baku is unique for urban thermal analysis. The city's climate is dry to semi-arid, with a very high solar loading during the summer months, also notable for its high central construction, large industrial and transport corridors, as well as its highly developed coastal area and historically significant oil-related land uses. Within the urban landscape there are smaller residential blocks, large arterial streets, storage and industrial space, reclaimed or redeveloped industrial areas and newer high rise areas. These forms, in relatively small spatial scales, generate big differences in the texture of the materials, shading properties, heat storage capacity and human interference. The general coastal area of the Caspian is also of high economic and environmental value, with studies highlighting Azerbaijan's vulnerability of coastal and strategic water resources to environmental alterations (Qadimli et al., 2026).

Azerbaijan is not only impacted by urban environmental stress via temperature. Energy consumption and other ecological externalities are connected to industrial/transport pressures as well. For instance, Arifzade et al. (2026) demonstrated the role of industrial and transport activity in shaping PM_{2.5} and PM₁₀ pollution in highly-urbanized areas. While air pollution and LST are different variables there are shared drivers of the variables, including spatial heterogeneity of green infrastructure, impervious land cover, and traffic intensity, amongst other variables. This strengthens the case for integrated (urban) environmental assessment and moving beyond viewing heat as an independent phenomenon.

The works of remote sensing in Azerbaijan are still relatively small in respect to the rapidness of urban changes. Amanova et al. (2024) analyzed urban heat conditions in Shirvan using Landsat and GIS, and found that the thermal conditions in intensively-built areas were unfavorable, while Bekirova et al. (2022) discussed methodological aspects of calculation urban heat-island indicators in densely-built areas. Later, Qadimli and Mammadov (2026b) presented the retention ability of LBDs with different sizes, colors, and heights in Luanda, highlighting the practical application of combining urban morphology and satellite-derived temperature data in rapidly growing urban areas. It is shown in these studies that a similar spatially-explicit approach is applicable for Baku, while still the detailed assessment of built-up densities and LST for the summer in the central urban corridor is required.

Thus, in the present study, we investigate how the urbanization (measured by current built up density) affects the spatial distribution of land surface temperature (LST) in central part of Baku city. The analysis intentionally emphasizes how different it is inside the urbanized zone, not the intensity of the urban-heat island compared to a typical rural site. The goal is to locate high LST values/dense built surfaces, and to find typical hotspot environments. The analysis focuses on three questions: which areas of central Baku experience a high LST in summer; how does the built-up density vary across the area; and where is there a correlation between high LST and high built-up density that creates locally significant hotspots? Three representative zones are also analysed to demonstrate the various urban shapes of industrial, residential, commercial and transport-oriented in the thermal landscape.

Changes in thermal regime caused by urbanisation are particularly relevant in cities with a combination of compact urban residential development and industrial activities, as well as transport system development and large-scale redevelopment projects. All of these processes shift the balance and distribution of materials that absorb, store, and reflect (redistribute) solar energy. Albedo, thermal inertia, shading and moisture availability and ventilation are all different for a large roof, an asphalt logistics yard and a compact residential block, all of which count in their local area as built-up. Therefore, an urban heat assessment based on administrative land-use categories alone might neglect the understanding of the underlying physics of the generation of district temperatures. Satellite LST can be used to directly monitor the cumulative thermal performance of these surfaces at the image acquisition moment and built-up density can be used to monitor the strength of construction that falls under the same urban fabric (Voogt & Oke, 2003; Song et al., 2020).

This is an issue that has implications outside of the realm of environmental mapping. Although LST is not a direct measure of human discomfort, the hotter the surface the more likely high surface temperatures will result in hotter microclimates, more cooling demand, more infrastructure weathering and less comfortable public

places. Thus, spatial clustering of hot surfaces could be used as an early-warning system for locating areas to focus on for more intense field monitoring during planning. This screening function is especially helpful in data-limited conditions where there are sparse meteorological sensor arrays. Identifying areas where heat from the ground surface and urban density meet can help better allocate field survey and urban greening and climate resilient investing (Zhou et al., 2019).

Central Baku is also a good example, because its urban morphology is also historically superimposed. It is the modern metropolitan scene, with petroleum-related industrial complexes, Soviet era residential and transport buildings, post-independence commercial growth, new high level building structures and coastal regeneration. These land-uses histories have generated abrupt differences in block dimensions, roof forms, street width, presence of an open space and vegetation cover. The result is a spatial heterogeneity, which implies that the thermal impact of urbanisation is not adequately described in terms of a single citywide mean. While a citywide average can be helpful for comparison between cities, it is less helpful in identifying specific corridors which, because of a mixture of built form and surface materials, may feature a concentration of thermal pressure. The present study thus focuses on intra-urban patterns rather than a binary allusion between rural and urban areas.

This emphasis is also addressing a pragmatic methodological problem that is associated with arid areas. Built-up land detection spectral indices may be found to have high values due to bright bare soil surfaces in sparse vegetation areas. However, other than taking a spectral index as the main measure of urbanization, the study derives built surface as a standardized measure through the use of the built surface product of the Global Human Settlement Layer. With this option, the thermal map can be overlaid on a conceptually different built-density map. The result itself is not a causal model but makes less circular the resulting model, which would happen if both the thermal and the urbanization variables are based on two or three reflectance variables. The approach is thus well suited for an exploratory assessment of the spatial overlap of dense built form and high summer LST.

The analytical contribution is thus triple. Initially, the scientists constructed the summer LST baseline for an 88.40 km² corridor in central Baku based on median of multi-scene Landsat 8-9, which is reproducible. Secondly, it represents GHSL built surface as a percentage density measure, and assesses its spatial correlation with the thermal pattern. Third, it transforms the city-wide overlay into its three detailed "hotspot zones" that can be understood vis-à-vis urban morphology. This shift from the regional context to the city-wide patterns and finally neighborhood scale hotspot images supports previous urban heat case studies communicative ability and meets the needs of the urban heatworkflow to the built-environment snaps of Baku (Ramos Zúñiga & Gomez Arredondo, 2025).

LITERATURE REVIEW

Land-cover conversion and urban morphology are indicated as strong influence factors of thermal conditions on the surface in the whole literature about the urban heat. Oke's (1982) city energy-balances framework revealed that surface heat storage and longwave radiative transfer and turbulent fluxes are modified by city built environment. These principles were later applied to spatially continuous observations made by later thermal remote-sensing studies, which related the surface expression of the urban heat to vegetation and impervious cover and morphology (Voogt & Oke, 2003). While the contrast between the air temperature at the canopy level and

satellite-measured surface temperature is significant, LST is especially well suited for capturing neighborhood scale air temperature differences that are directly related to the land surface materials.

Leaves, imperviousness and vegetation are highly investigated predictors of LST. Weng et al. (2004) demonstrated an interpretation of the urban thermal patterns by using the relationship between signs of vegetation abundance and surface temperature: the surface temperature was generally lower in the densely vegetated zones than in the impervious and sparsely vegetated zones. Thermal signature change indicates the change of land-use and land-cover due to urbanization in the time series analysis carried out by Fu and Weng (2016). These data can help substantiate using surface temperature derived from satellites as an indicator of thermal modification associated with urbanization, particularly when combined with another metric of built form such as spectral indices.

Such an independent measure is built-up density. Song et al. (2020) analyzed 21 cities in China and found a systematic influence of building density on LST, as well as demonstrating the impacts of climatic setting on this relationship. Their findings can pertain to Baku as a dry climate might intensify the temperature difference between built-up and non-built-up areas. Estoque et al. (2017) also demonstrated strong relationships between impervious surface density and configuration and mean LST in the mega cities of Southeast Asia. The results suggest that urban heat is not only dependent on whether a pixel is deemed to be urban or not, but also on the aggregation and space pattern and the density of built materials.

The use of standardized Earth-observation products and cloud computing are becoming common approaches for urban heat research. By combining a massive repository of satellite imagery with server-side processing and reproducible script writing, Google Earth Engine has emerged as a tool used widely for planetary scale geospatial analysis (Gorelick et al., 2017). This simplifies the technical process of filtering multi-scene Landsat collections, using cloud masks, extracting surface temperature and building seasonal composites for urban thermal applications. It is useful for studies where the processing must be uniform over the diverse urban landscape, instead of being an interpretation of one image.

The aforementioned Villahermosa study by Ramos Zúñiga and Gomez Arredondo (2025) serves as a methodological precedent that can be directly applied. The authors mapped the surface urban heat patterns using Google Earth Engine (GEE) and thermal satellite data, and they analyzed some of these hotspot areas with high infrastructure density, commercial facilities and high paved surfaces. Their interpretation at the zone level proved the communicative importance of shifting from interpreting a thermal image from the city scale to the hotspot scale. The visual logic used is similar to that used in the foregoing San Jose study, except that instead of a rural comparison framework, the built-density framework was used, since the issue under investigation in the present Baku study relates to variation within the already built-up center of Baku.

The Azerbaijani case studies underline the need to consider local context. The study by Amanova et al. (2024) indicates a significant spatial heterogeneity in the thermal space in Shirvan city and the river-side zones are relatively favorable. Bekirova et al., (2022) stressed the importance of systematic indicators in compact urban setting. On a smaller spatial scale, Qadimli and Mammadov (2026b) applied remote sensing methods in the Shahdag National Park to develop the priorities for NbR and green finance, providing an example of how geographic indicators can be converted to environmental finance priorities. While ecosystem restoration and urban heat are different

applications, the common thread is that through the power of spatial evidence, spatial information can be used to direct interventions, rather than policy.

Looking at the economic implications of urban heat also links to the Green economy literature. Increased surface and air temperature may lead to greater cooling demand, stress on infrastructure, and exposure to heat; mitigation solution may include capital investments in various approaches such as urban greening, reflective materials and energy-efficient buildings and public space redesign. Measurable environmental benefits can pave the way for targeted investment, Sadiqov et al. (2026) speak about the role of green-finance instruments in supporting solar-energy development in Azerbaijan – this financing-logic can be expanded to urban climate adaptation. In this context, locating where thermal pressure can occur is a climatological job, and ultimately a prerequisite for urban resilience expenditure prioritisation.

In spite of these developments, three gaps are still pertinent to Baku. First, many studies that address urban heat have been focused on the contrast between city and rural areas instead of heat heterogeneity within dense urban fabric. Secondly, spectral built-up indices may also give reasonable proportions of bare soil and built surfaces, in the case of dry environment, independent built surface products can be used for validation. Thirdly, hotspot maps aren't always accompanied by a much more detailed analysis of kind of urban forms that are producing a signal. The present study is an attempt to solve these deficiencies with a tri-fold approach: a blend of Landsat LST with Global Human Settlement Layer built-up surface product, a clear joint-hotspot rule and a detailed inspection of three representative zones, using high resolution cartographic views.

Urbanization and the surface energy balance

The surface energy balance is modified in several related ways due to urbanization. In general, under comparable conditions, natural or semi-natural surfaces expend more energy into latent heat in the presence of moisture while impervious urban surfaces are less able to allow for evapotranspiration and reflect energy into sensible heat or storage. The 3D surface area also increases as a result of buildings, which have a larger surface area are able to absorb more heat, and urban canyons change the exchange of shortwave and longwave radiation. After direct solar input, the effects of urban form are energetically explained by Oke (1982) and the reasons presented for this to happen. The present study does not require a full energy-balance model and uses daytime satellite LST, but the locations of the observed spatial pattern are indicative of the same physical processes.

The properties of the surface materials are also critical. Reflectances, emissivity, heat capacity and conductivity are different for asphalt, concrete, roofing membranes, compacted soil, and metal roofs. Their temperature response is thus highly influenced by the time of overpass by the satellite as well as by recent weather. Even though there may be a different radiative response, if it is bright and dry, a surface with a different reflectivity may have a different radiative response than dark asphalt, both of which surfaces can become stressful in the summer when the solar loading is high. This accounts for the non-uniqueness of LST when only land-cover categories are used. However, thermal remote sensing captures the collective effect of material properties, surface moisture, shading and atmospheric influences at the resolution of the pixel (Voogt & Oke, 2003).

The material effects are further influenced by urban geometry. High rise districts are able to produce a large surface area shade during part of the day, but also minimise longwave heat loss and street level

ventilation. Often low rise industrial areas have smaller vertically covered areas and significantly larger continuous roofs and paved service area. Thus, urban heat island surfaces, at a given overpass time, are not necessarily denser urban areas. Thus, the effect of building density on LST can change across different climatic and urban contexts (Song et al., 2020), making it important to consider these effects in conjunction with the nature and density of urban surfaces. Such is the Baku analysis which considers built-up density as a notable explanatory fold, not as explanations and exhaustive explanation of thermal variations.

Built Up density, imperviousness and urban morphology

Built-up density can be helpful as it measures the built-up intensity of an area within a defined spatial unit. Unlike the binary sense of urban or non-urban, a density surface can help to reveal the sparse development and cells dominated by units and associated built structures. This difference at the neighbourhood level is relevant for heat effect, with high built fraction potentially linked to a decrease in the exposure of soils and vegetation, an increase in heat storage and the amount of impervious cover. Estoque et al. (2017) showed that, along with the percentage of built-up land cover in the scene, the configuration of urban land cover is a factor affecting the LST, and that the composition of urban land cover (rather than merely its percentage) also has an impact.

An attractive advantage of using the Global Human Settlement Layer for cross sectional analysis is that it is independent of the Landsat thermal band that retrieved the LST. The GHS-BUILT-S product estimates the built surface on a regular grid and is designed to be analyzed in comparative mode in time and space (Pesaresi & Politis, 2023). Built surface can be converted to a percentage occurring in each 100 m cell, creating a simple intuitive indicator where built surface near to 0% means low constructed surface and high built surface near 100% indicates that the cell is dominated entirely by built surface. This measure does not define the building height or the floor area ratio, but can be used as a good indicator to detect the horizontal built-up area that can change the surface thermal characteristics.

One drawback to any density calculation method is that it can combine surfaces that have widely differing thermal properties. Two cells having the same built percentage could have different proportions of tower blocks and warehouses, small houses, shaded courtyards and roads. This means that their respective LST can differ for the same density. GHSL is not the only one who has this problem; urban morphology is multidimensional. Built density is thus most useful when as one of several layers in an overall interpretation. In the current study visual interpretations are completed from high resolution basemaps as well as detailed Zone A–C maps to explore the rationale for varied thermal interpretations within similar density conditions.

Thermal remote sensing and seasonal compositing

Landsat has played a pivotal role in urban thermal research due to its spatial resolution that allows to resolve major neighborhood patterns and possess a long history. Weng et al. (2004) showed the value of Landsat-derived temperature for examining relationships between vegetation abundance and urban heat. Later research has employed the archive to document changes of land cover and LST occurring with time, and this has shown that the thermal changes due to urbanisation can be seen over many decades (Fu & Weng, 2016). The Collection 2 Level 2 surface-temperature product makes this workflow easy, since it provides a consistent temperature band from which a temperature can be derived using published scale factors

without the need to repeat the full atmospheric-correction chain for every given study.

Seasonal compositing can be useful when the research question is to find the representative pattern for the warm season, and not for the temperatures of one abnormally warm or cool day. A median composite minimizes the impact of anomalies, such as artifacting from individual scenes, masked-out clouds, and is resilient to anomalies that only occur on a short-term scale. This comes at a cost because the value obtained is not representative of one particular meteorological instant. It should be interpreted as a multi-informational source of the persistent spatial thermal structure of the season selected. This distinction is crucial in interpreting the map of the 2024 Baku surface: not a continuous record of heat exposure, but areas where they repeatedly find themselves in a warmer or colder position in the summer distribution.

2. Multi-scene workflows are now more reproducible in Google Earth Engine by being attested with scripts using filters, bitwise quality masks, band scaling and compositing (Gorelick et al., 2017). Cloud computing also makes it possible to repeat the analysis if thresholds, dates or study boundaries are updated. Repeatability is particularly useful in urban studies as the temperature at a particular location in a city may vary slightly with minor difference in the preprocessing. In this study, the Collection 2 QA_PIXEL layer and the official ST_B10 scaling parameters are used, ensuring a transparent procedure which can be repeated for other cities or future periods of Baku.

Evidence from dry, coastal and industrial urban environments

Dry cities have different thermal behaviour compared to humid cities because of the possibility of achieving high background LST with bare soil, little vegetation and low surface moisture. Teini eroded land and the areas that have not been constructed can be similarly ambiguous as in vegetated environments. Deserted bare ground is often very hot and areas of irrigated vegetation in urban sites are sometimes cooler than adjacent areas of undeveloped lands. Hence one of the limitations of the present study that the urban heat is not defined merely as a difference between the urban and rural temperature. The study question is now if there is spatial association between high LST and high density of built up/urban development within central Baku and where is the relation more prominent.

Coastal location adds additional complexities. Water bodies can alter local atmospheric flow, and local surface temperatures, but the extent and influence of coastal cooling is related to wind, topography, urban geometry and time of day. The urban southern coast shore of the Caspian Sea, in Baku, is faced by the high urbanization and industrial areas. Thus, integration with the sea can not be used as a determinant to low surface temperature in neighboring built areas. The current study contributes to a greater understanding of the thermal dimension of the Caspian coastal urban interface, which was previously highlighted by Qadimli et al. (2026) in the context of both economic and environmental significance.

Particular emphasis is warranted for industrial and transport applications, as the thermal and environmental load can interfere with each other. Major transport corridors contribute asphalt surfaces and heat emissions from vehicles; large industrial parcels often feature highly developed roofs and impervious paved yards along with internal road systems. Arifzade et al. (2026) show that industrial and transport reasons can be significant in comprehension of a particular pollution in Sumgayit and Almaty. The environmental factors listed in that study are different pollutants than LST but the same spatial factors indicate that multiple environmental factors can be experienced in industrial and transport zones at the same time. This

contributes to the integrated screening of heat and air quality and land-use intensity in future research in Baku.

Azerbaijani context and research gap

Local evidence shows increasing but disjointed evidence. Bekirova et al. (2022) added methodological studies on heat-island indicators in the urban environment and Amanova et al. (2024) showed how the combination of Landsat and GIS can be used to find the thermal difference of Shirvan. These studies reveal that heat indicators from satellite data can be applied in Azerbaijan and intra-urban differences can be identified at Landsat resolution. The city of Baku is, however, a metropolitan city and its history is associated with the industry and its coastal morphology, so a specific study of built density would be justified.

Two recent geospatial studies, that of Qadimli and that of Mammadov, offer methodological context. In their Luanda analysis they associated urban expansion with the distribution of heat at the Earth's surface and vegetation pattern, thus showing how surface heat distribution together with the description of the land-cover can be used to describe spatial consequences of urban expansion (Qadimli & Mammadov, 2026a). In their study about Shahdag National Park, they analyzed the needs for green finance-related nature-based restoration activities through remote sensing and prioritized them (Qadimli & Mammadov, 2026b). These applications collectively show a general research approach that uses spatial indicators as a means to define environmental management and investment priorities.

Another aspect of the present study, which relates to planning, is the connection with the green-finance debates. Sadiqov et al. (2026) explains financial instruments in accelerating solar-energy development in the Azerbaijan. While distinct types of projects are necessary for urban heat mitigation, the financing logics are similar—location-dependent environmental returns can be used to design the heat-specific investment portfolio. Capital is required for cool roofs, energy efficient retrofits, shade trees and climate-sensitive redevelopment, as well as to support shaded transit infrastructure and urban trees. Later, when combined with population exposure and socioeconomic vulnerability and cost information, a high resolution hotspot map can, thus, serve as one input for prioritizing projects.

It is now possible, therefore, to specify the research space more precisely. Baku has a multi-scene Landsat summer LST composite and a quantitative built-surface density layer, but no published, neighborhood-scale assessment where overlap between the two layers is interpreted in detail via hotspot maps. The present study aims to correct this lack and, at the same time, be very conscious about the issue of causality. Does not do an econometric coefficient estimation but do a spatial proposition testing: very high built density areas are expected to be over represented among the hottest areas, but amount of temperature depends on morphology, land use, vegetation and local surface properties. Such a framing enables the analysis to be scientifically viable and practically useful.

MATERIALS AND METHODS

Study area

The study area, which has an area of 88.40 km², is located in the central part of Baku, Azerbaijan; it was mapped manually in Google Earth Engine to include the entire urban corridor starting from western and south western sides of the central city and extending to the eastern part through the urban fabric at the bay-front. The border is analytical not administrative, it is designed to capture the main built-up urban areas and coastal urban areas that are pertinent to the research question and prevent large peri-urban areas which might

dilute the intra-urban heat signal. The polygon is home to elements of Səbail, Yasamal, Nəsimi, Nizami and Xətai districts and encroaches on dense residential neighbourhoods, main transport corridors, industrial and commercial land, areas for redevelopment and coast line infrastructure.

The climatic and morphological environment of Baku is very favourably for the LST assessment in the summer season. Areas with high solar radiation, low summer precipitation and widespread impervious surfaces and large anthropogenic surfaces provide conditions where local contrast of the roof and paved areas, bare soil, vegetation and water can result in significant differences in surface temperatures. The Caspian shoreline does intersect the study area, however, permanent water pixels from the thermal data were excluded from the analysis to ensure that the LST range referred to land surface and not to the sea surface which is much cooler. The analytical boundary shown in Figure 1 is the final result on an OpenStreetMap base layer.

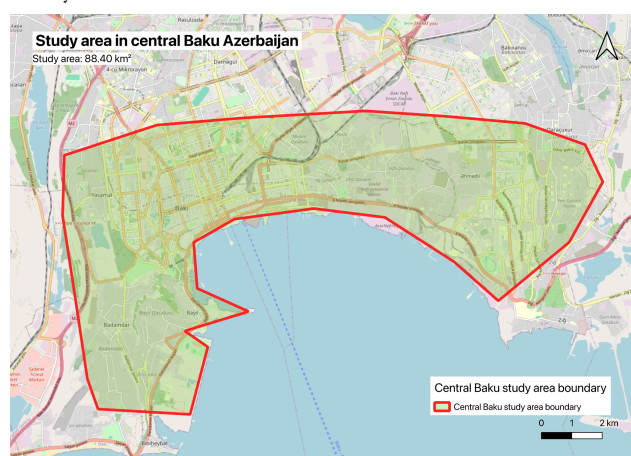


Figure 1. Location and spatial extent of the study area in central Baku, Azerbaijan. The delineated analytical area covers approximately 88.40 km².

The research area was planned to capture the continuous urban fabric of the city center, without fixing on a particular administrative area. It is significant given the transgression of municipal sub-districts in the case of thermal processes and built morphology. The polygon encompasses the central bay-front and largest axis of east-west transport, as well as high-density neighborhoods, industrial and post-industrial lands, and the urban sprawl of the west and southwest. Sea itself was not masked in the surface level in the thermal analysis, permanent water was masked. Thus, the 88.40 km² value represents the demarcated study polygon, and the temperatures statistics (valid land pixels in masking mode).

The chosen extent also captures a range of urban morphology with a meaningful association in one climatic setting. The western side limits have mixed high and low rise development, the middle corridor are areas of dense residential/ commercial fabric, and the eastern /northern sides of this block are areas of larger parcels mostly industrial, warehouses and transport. This intraspecific diversity is important as it allows the comparison of surface-temperature variation that does not involve the much greater climatic and topographic variation seen with the use of a reference set in distant rural areas. Thus, it is a method of IntraUrban morphology Assessment instead of a traditional urban heat-island intensity calculation.

The coastal influence is possible due to the location of Baku on the western coast of the Caspian, but any sea-breeze effect was not considered in the study. Additional meteorological information and time-specific analysis would be needed to incorporate the effects of

coastal distance, wind direction and atmospheric stability. Instead, coastal location is assumed with the geographic context of patterns seen in Figures 2-7. This distinction makes it possible to avoid wrongly assigning low or high LST to the sea without solid proof and makes it possible to concentrate on the spatial association among built density and surface temperature in the study.

Data sources and software

The analysis included surface-temperature data derived from Landsat data, built up surface derived from GHSL data, and auxiliary cartographic layers. Landsat 8 and Landsat 9 Collection 2 Tier 1 Level 2 imagery was chosen due to the science products of surface temperature measured and atmospherically corrected surface reflectance, which are useful for urban thermal analysis. Images were only collected during the period June 1 to August 31, 2024, and only for those scenes of which no more than 30% of the entire scene was covered by cloud at the time of the scene. In total, 13 Landsat scenes made up the composite after filtering and quality masking by pixel. Data was filtered, masked, scaled, composited and exploded to rasters using Google Earth Engine and cartographic design and visual interpretation using QGIS.

Table 1. Analytical roles and data sources.

Dataset / source	Specification	Analytical role
Landsat 8 & 9 Collection 2 Level 2	June–August 2024; 30 m LST grid; 13 filtered scenes	Summer land surface temperature
GHS-BUILT-S R2023A	2020 epoch; 100 m built-up surface grid	Built-up density (%)
ESA WorldCover v200	10 m global land-cover product	Permanent-water mask (class 80)
OpenStreetMap / Esri World Imagery	Contextual basemaps	Study-area and hotspot interpretation
Google Earth Engine / QGIS	Cloud processing / desktop GIS	Processing, export and cartography

This Landsat scaling process was conducted in accordance with the product specifications of collection 2 level 2 Landsat products (U.S. Geological Survey, n.d.). Built-up surface was derived from GHS-BUILT-S R2023A, which incorporates information in Landsat and Sentinel-2 and estimating built surface over time (Pesaresi & Politis, 2023). This is crucial in Baku, since bright bare soil and building surfaces may lead to spectral responses that are similar to the built material itself when NDBI are used.

To avoid any flakey data moving from scene selection to raster export, all processing was accomplished using Google Earth Engine. Satellite data was downloaded as Landsat 8 OLI/TIRS and Landsat 9 OLI-2/TIRS-2 Level 2 Collection data and subjected to filter based on study area and time (01/06/24 to 31/08/24). These were filtered without pixel level masking using a scene level cloud-cover filter and a threshold of 30. Of those scenes, 13 had valid observations in the summer composite, following the above-mentioned filters. In addition to the use of Landsat missions, temporal sampling was enhanced and the Collection 2 processing conventions remained consistent throughout both missions.

In order to provide this GHSL layer; the measurement of built density that is unaffected by the same Landsat composite used to produce the temperature layer, was selected. The surface harmonized estimate GHS-BUILT-S R2023A is suitable for urban built surface representation of the horizontal extent of built-up development

(Pesaresi & Politis, 2023). Only an auxiliary water mask from ESA WorldCover was used; the permanent water class 80 wasn't included in the display and the statistics of LSTs. High resolution imagery and OpenStreetMap were not used to derive temperature data or built density, but were added as cartographic context for the geographic understanding of the types of urban environments represented by the hotspot clusters.

Subsequent to Earth Engine processing, projection management, symbology, figure composition and detailed visual inspection were performed in QGIS. The project coordinate reference system was WGS 84 / UTM zone 39N (EPSG:32639), which was using metric units that were appropriate for scale bars and local distance interpretation within Baku. It is an intentional separation: Earth Engine aims at a reproducible computational environment for raster operations; and QGIS aims at cartographic production with more precise control over figure layout, labels, transparency and publication graphics.

Landsat preprocessing and LST retrieval

The Landsat QA_PIXEL bit flags were used to remove clouds, cirrus, dilated cloud pixels and clouds shadows. From this stored digital number the thermal band ST_B10 was then converted into Kelvin using the scale factor and offset from the official-scale values and finally into degrees Celsius. Step performed on each Landsat 8, 9 image:

$$LST(^{\circ}C) = (ST_B10 \times 0.00341802 + 149.0) - 273.15 \quad (1)$$

The summer LST collection was used to calculate a median composite. By selecting the median instead of a single-date image, the impact of the residual cloud contamination as well as the scene-specific variation in the atmosphere and short-lived anomalies was reduced, while maintaining the overall spatial pattern of summer surface temperature. There was masking for ESA water class for permanent water (as otherwise the lower end of the temperature would have been dominated by coastal water). The last exported LST raster was masked within the study extent, and mapped according to a continuous cool to warm colour ramp.

All dilated cloud, cirrus, cloud and cloud-shadow bits were removed from the temperature bands by the QA_PIXEL mask. No attempt was made to fill coding masked pixels from spatial neighbors. Rather, the seasonal median value was computed at each site based on the available valid data. This means no synthetic temperatures are added to the composite, but with fewer valid observations, this could result in less temporal representativeness for these pixels. The remaining scene set retained is for the summer, as this time of year is relatively dry and cloud cover is less common in Baku.

The surface-temperature conversion is based on the Collection 2 Level 2 specification. The value of ST_B10 that is stored in the value field is multiplied by 0.00341802 and the result subtracted from 149.0, the result multiplied by 273.15 (U.S. Geological Survey, n.d.) then used to display temperature in degrees Celsius. This study hence does not estimate emissivity separately from NDVI, nor use an extra single channel emissivity algorithm. An official LST product (Level 2 product) can help ease the user defined assumptions and allows replication of the final LST, but uncertainties inherent in satellite retrieval and atmospheric inputs are still present.

Use of a median summer composite was used, rather than a mean because extreme results and remnants of artefacts influence the arithmetic average disproportionately. Established median value is the middle value, in the case of summer observations, of all valid land

pixels. This option is used to aid in the goal of diagnosis persistent relative thermal structure. It also means the so-called temperature range reported (30.73–52.60 °C) does not represent the lowest and highest temperature attained on each date of summer, but rather the surface temperature range. The differentiation is reflected in the results and discussion.

Built-up density calculation

The built-up density has been extracted from the Epoch 2020 of GHS-BUILT-S R2023A. Band selected is built surface area in m² per 100 m grid cell. The built-up density was calculated by Equation 2 as percentages based on cell area, since the size of a cell is 100 m × 100 m, or 10,000 m². The result can be, in theory, between 0% (for cells which are not built at all) and 100% (for cells which are built entirely).

$$\text{Built-up density (\%)} = (\text{built surface area} / 10,000 \text{ m}^2) \times 100 \quad (2)$$

The 2020 GHSL epoch was kept since it is an observed, standardized reference layer and is close enough in time to the 2024 thermal observation period to allow a cross-sectional urban morphology evaluation to be made. Analysis is therefore based on the spatial intensity of the built surface that is already in place rather than a four-year temporal change calculation to interpret urbanisation. This differentiation is significant as the current study focuses on the relationship between the present built environment and the summer thermal pattern of 2024, and long-term urban expansion is addressed through a multitemporal study which is scheduled for future work.

The density of the built-up area was calculated from the derivation of an area to a dimensionless percentage, for direct interpretation of the settlement density. So the built up density for a 7,000m² cell is 70%. It was observed that in the study-area range extends to the extent of about 98.04% and some of the GHSL cells are almost fully covered by built surface. Whereas, quantities close to zero will be found in the intersections of the grid with open space, water adjacent land or other non-built surfaces. The density map is coarser than Landsat LST and, like Landsat LST, should be used at a neighbourhood level and not at a building level.

During the 2020–2024 time window, the temporal mismatch is considered to be a near-contemporary approximation of the cross section. No assumption is made that the built environment has not changed over this time, and the difference between dates is not taken as indicative of growth over the 4 years. This is because the selection is based on the availability of an observed GHSL epoch in the vicinity of the thermal analysis year. Major construction that took place after 2020 may thus underestimate the built density of areas in 2024. However, this uncertainty becomes important especially in redevelopment zones, and the image interpretation of the close-up image is carried out taking this into account.

However, there are conceptual differences between built density and population density/building volume. A warehouse district may have a high built area, but few inhabitants, and a tower district may have many inhabitants, but a small built area. The study thus adopted the physical set of indicators on land surfaces: built-up density; which are also indicators of the demographic variables. The current layer should be overlain in future with population data, or building volume data, to identify high temperature areas with varying numbers and vulnerabilities of potential affected populations.

Joint hotspot delineation and zone selection

Joint built-up–heat hotspot was defined by two-threshold rule where the transparency was maintained. High-temperature cells had a median summer LST above 45 °C, and high-density cells had a GHSL built-up density above 70%. These conditions were intersected to

determine areas where there was heavy thermal loading coupled with high built up surface density:

$$\text{Hotspot} = 1 \text{ if } LST \geq 45 \text{ }^{\circ}\text{C} \text{ and built-up density} \geq 70\%; \text{ otherwise} \\ \text{Hotspot} = 0 \quad (3)$$

The thresholds were chosen as criteria for an operation, rather than the general climatic thresholds. They were designed to separate the higher density and higher temperature side of the study area, and to yield a simple set of priority clusters that could be interpreted. The hotspot layer is meant to be used at a neighborhood and block level due to the differences in native resolution between Landsat LST and GHSL built-up density, and should not be used as an engineering-level parcel-level map. Three representative clusters were then selected based on the spatial prominence, and contrast urban morphology: (Zone A in central coastal industrial corridor, Zone B in eastern urban corridor and Zone C in northern Urban /industrial corridor).

Joint threshold is designed to be rather strict. There are two LST cutoffs that help differentiate the upper warm part of the summer composite: 45 °C, and 70% built-density, which is the differentiating cutoff for cells with a dominant built footprint. The logical intersection stipulates that both conditions be met, which means that hot bare land (where there is little land use) and dense urban cells that can stay below the thermal threshold are not included. This is crucial for a dry city because exposed non-urban or construction soil can be thermally intense but is not the built-density mechanism being studied.

Based on three criteria – space continuity, interpretability and the contrast in urban form – three representative clusters were derived from the resulting mask. Zone A is the largest zone in the group and is the central coastal area of industrial and large parcel related imagery. Zone B is a more concentrated east hotspot that combines a high density of buildings and urban development. Zone C is a northern cluster, with its surrounding context a mixed use, low-rise and industrial/warehouse setting. The zones are illustrative and not intended as a full hierarchy of all hotspot pixels and the zones are interpretive visualization areas and not official admin boundaries.

The threshold mask is not associated with a significance test. It is used for screening or visualization. The added benefit of a threshold based screening is transparency and ease of reproduction, but varying thresholds would yield varying number and size of the clusters selected. A percentile based sensitivity analysis would be a good addition. Fixed thresholds were kept for this study as they are directly interpretable in physical units, and fall to a straightforward question: where very warm summer surfaces and very high and dense built footprint converge?

Cartographic and visual interpretation

All thematic rasters were exported from GEE and compiled in QGIS. High resolution satellite data is used as a semi-transparent thematic map over a high resolution satellite base map at the main maps. The map in the study area was created using Open Streets Map. To accurately display scale-bars, the QGIS project was shown in WGS 84 /UTM Zone 39N (EPSG:32639). Additionally, zone maps were created at increasingly larger extents to be viewed in conjunction with the hotspot map, such that roof footprints, large paved surfaces, storage spaces, roads and the macro-scale surrounding residential fabric can be visually compared with the hotspot map. The zone interpretation is descriptive and spatial, it designates possible configurations of the land surface, associated with the thermal pattern, but does not pretend to arrive at causation at the building level.

To have visual comparability, the same symbology was applied to the citywide and detailed maps of LST through the cartographic interpretation. The blue colors indicated cooler temperatures, while the yellow, orange and red indicated warmer temperatures. Built density was mapped with a yellow–red built density ramp from low to high. The binary mask was overlaid as a red layer on top of LST map to identify the combined hotspot map which allows separability of the combined screening result from the continuous thermal background. Scale bars and north arrows were inserted in QGIS and source notes are used in each figure to define the analytical and contextual data used.

Visual interpretation was done on high-resolution background imagery, whereby the dominant surface type in the three zones was identified. A morphological description of the built environments associated with the raster signal is produced, but not field verified. At this level, large roofs, industrial yards, transport corridors, construction sites, residential blocks and vegetation can be discerned and reasonable hypotheses posited to account for spatial temperature variations. There is a need, therefore, for the use of the ground photographs as a layer of validation and communication that should validate the nature of the site as determined by the remote sensing analysis.

A workflow was developed that allows the seven maps to be reproduced from the same analytical map layers. Thus, figure 1 sets out the study boundaries; Figure 2 illustrates the LST surface; Figure 3 the built density; and Figures 5–7 show a progressive increase in the scale of the zones A–C respectively. This hierarchy offers a useful way to avoid a common issue with urban remote-sensing studies, where the reader is presented with a citywide raster, but is not able to correlate the warmest pixels with the identifiable urban form. These detailed maps consist of a set of maps that are related to physical landscape but do not modify any of the values on the underlying raster maps.

Analytical scope and limitations

A few methodological limitations were taken into account in interpreting the results. Landsat LST is the temperature of the surface skin at the time of satellite overpass, and is not meant to be confused with an air temperature experienced by humans. The seasonal median is not intended to represent individual heatwaves but is used to help depict spatial pattern because it is robust to the day-to-day fluctuations. The GHSL built-up layer is at a coarse resolution and shows the density of built surfaces, not building height or the type of material or 3D form of buildings. Lastly, the thresholds used as the ‘hotspot’ are screening thresholds and not statistically optimized thresholds. Such limitations are discussed and will drive future research to be done with the air-temperature datasets, building-height and multitemporal urban expansion indicators.

RESULTS AND DISCUSSION

Spatial distribution of land surface temperature

The LST map for summer 2024 shows significant heterogeneities in thermal conditions in the study area of 88.40 km². Spatially localized regions with surface temperatures corresponding to vegetated or moist surfaces along with regions where the land cover is significantly distinct from extensive impervious fabric present cooler areas at the range of ~ 30.73 °C to 52.60 °C. Warmer orange to red surfaces on the other hand are found covering extensive areas of centrally and eastern developed areas, as well as in the form of a localized band of high temperatures around industrial, transport, and high roof areas.

The urban thermal pattern is not uniform as can be seen in Figure 2. Certain neighborhoods, which are densely inhabited, fall into late intermediate temperature classes, and individual industrial and transport-related surfaces at the top of the distribution. This concurs with the reasonable physical notions that LST is influenced by the urban density as well as by the roofing materials used, extent of pavements, surface moisture, shading, vegetation, and geometry of the surrounding urban fabric. This intra-urban contrast has been reported in other Landsat-based studies that show higher LSTs for impervious or less-vegetated surfaces compared to greener surfaces (Weng et al., 2004; Estoque et al., 2017).

A similar example of thermal contrasts based on zones of cooling or heating was found by Ramos Zúñiga and Gomez Arredondo (2025), for the case of Villahermosa, in which large plots of commercial, industrial and asphalted surfaces left conspicuous thermal anomalies. However, the current analysis does not attempt to identify each warm pixel as a formally defined urban heat island as compared to a rural location. Similarly, Figure 2 is interpreted as a surface-temperature field of intra-urban areas and is analysed with respect to the built-up density in the next few figures.

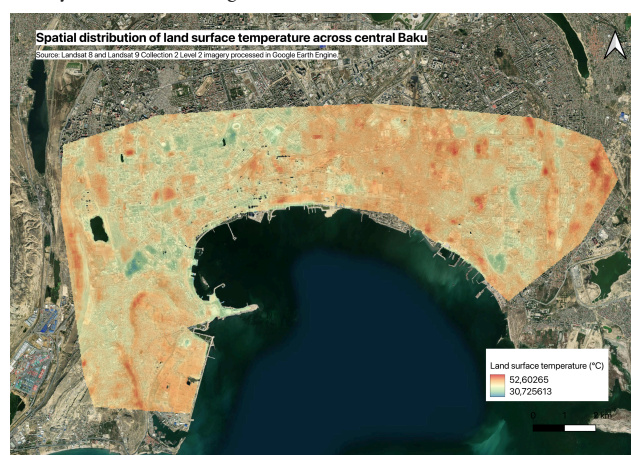


Figure 2. Spatial distribution of summer 2024 land surface temperature across central Baku derived from Landsat 8 and Landsat 9 Collection 2 Level 2 imagery.

The larger thermal gradient is not dominated by a center-to-edge pattern, but rather is a mosaic of warm and cool areas. This is in line with the mixed morphology of the center of Baku. Within the study area, which is somewhat dominated by highly-developed zones, the thermal response can vary from block to block. Several relatively cooler areas are found in the western and central portions which correspond to areas of different surface or greener, moister land, while a large number of warm parcels are found in the eastern and northern portions. These can tend to be high if it's a large continuous surface (and not every dense residential block). This trend reinforces the theory that high probability of high LST is found in the urban environment while variations in material and morphology control the local magnitude.

The minimum value of the composite (~30.7 °C) is a temperature characteristic of the spatially limited areas and should not be compared with summer average temperatures of central Baku. These cool pixels indicate surfaces with a median thermal response that were considerably lower than areas in the vicinity. The top one, around 52.6 °C, is also a surface value and not one which can be interpreted as a city value. The temperature difference between the minimum and maximum values for this map (21.9 °C) shows the extent of intra-urban surface heterogeneity that would be masked by a single average. Satellite LST proves very useful for screening purposes to

plan, and this is one of the reasons that such heterogeneity exists (Zhou et al., 2019).

Based on the comparison with previous works, it can be concluded that the Baku pattern is physically valid. Weng et al. (2004) highlighted that the thermal surfaces properties in the urban areas are often considerably dependent on the type of urban greenery, and Estoque et al. (2017) also found that the mean LST is related to the density and distribution of impervious surfaces. Built context and land-cover composition come into interaction on a neighbourhood level, as seen in Baku where cool and warm surfaces are within the same urban corridor. The map can thus be interpreted as evidence for a differentiated not uniform perception of urban heat: mitigation action prioritisation cannot be based on intensity of development alone, as must follow surface conditions as well.

It is important to interpret the surface-temperature values given these conditions of satellite overpass however. The high LST of roofs and pavement does not necessarily mean that humans were exposed to the same temperature air, under full sun the temperature may be much higher than 50 °C. However, even if day time LST is moderate the night time cooling might be poor. Voogt and Oke (2003) have highlighted this difference in urban surface and atmospheric climate. It is therefore best to think of the current map as providing a spatial indicator of daytime surface heating potential which can help inform subsequent microclimate and public-health measurements.

Spatial pattern of built-up density

The density ranges from 0 to almost 98.04% bu in the study area. As shown in figure 3, high values for built-surface fraction are prevalent along the central urban corridor, albeit more blocky than the LST surface as the GHSL data is summarised at 100 m resolution. The built-up areas are dense in both residential and non-residential settings such as compact residential areas, large commercial or industrial landscapes and transport-based development. Lower-density cells are related to open land, large undeveloped and transition parcels, green spaces and some gaps along the coast and infrastructure.

The contrast of Figures 2 and 3 is analytically fruitful. In fact, high built-up density does not necessarily lead to the actual absolute highest LST in each and every locality, suggesting the importance of local morphology and surface composition. Many of the warm areas, however, are found in or close to well-developed convective complexes. This spatial correlation is consistent with Song et al. (2020) who showed building density has systematic effects on LST, and consistent with similar work, which showed aggregates of impervious surfaces and impervious-surface density are positively correlated with thermal loading (Estoque et al., 2017).

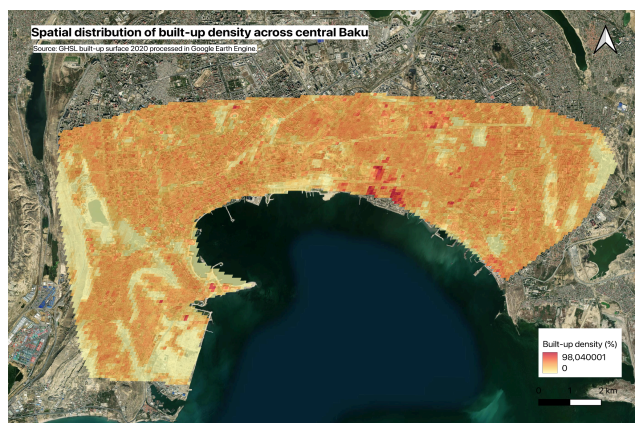


Figure 3. Spatial distribution of built-up density across central Baku derived from the 2020 GHS-BUILT-S R2023A product.

It is significant that the built-density surface is able to validate that a lot of what is analyzed is structurally urbanized and that central Baku is strongly built urban in most parts of the study area, yet it is also able to see some significant differences in the amount of horizontal building that has been done. The highest values comprise a patchwork of cells linked to dense blocks, industrial complexes and large building footprints. The lower percentage areas include water adjoining, spaces where open land forms part of a 100 m cell and broad undeveloped parcels, any 100 m cell in which a built up footprint only occupies a portion of the cell. The maximum observed is approximately 98.04% which suggests that there are certain cells that contain very little non-built surface.

Spatial correlation with LST is high but not full. From Figure 2, there are several high density cells that are in relation to warm colors that support the central research proposition with other dense cells being near the center of the LST distribution. This difference theoretically is to be expected since built density is a measurement of area and not surface reflectivity, roof material, building height, tree canopy or shade. Song et al. (2020) demonstrate also that building density is another key factor influencing LST, which will be different depending on climatic and urban conditions. The Baku maps thus illustrate as well as attest to an association, and also support the need for a multivariable interpretation.

The GHSL resolution also includes coarse resolution blocks that are visible and do not necessarily represent real parcel boundaries. In a 100m cell other elements of a settlement, such as multi-building structures, roads, courtyards and patches of small vegetation, can be present. Whereas the Landsat thermal pixels are finer and localized hot surfaces may exist in a GHSL cell with average built percentage less than the selected threshold. Together, the two data sets are two views of related but differently granular aspects of the city. They are best combined to define larger building clusters and are not as effective to a particular density value of one building.

Another way of looking at this from an urbanization point of view is that the density surface reminds one that built intensity is not equivalent to recent growth. The map shows the total 'material footprint' of development up to the GHSL 2020 epoch. There may be high levels of urban development in the more historic central districts, although the contemporary scale of development may be low, or high levels of activity in the more active redevelopment areas may not have been apparent in 2020. This temporal differentiation has relevance to the reworked article title, which is based on urbanization as a conceptual process and built-up density as the operational spatial indicator of usage in the empirical analysis.

Hotspots of built-up and heat.

The joint hotspot mask consists of only one subset of localized areas that fulfill the two major conditions, namely $LST \geq 45^\circ\text{C}$ and built-up density $\geq 70\%$. This intersection is more selective, than both maps and is therefore helpful in identifying areas where the strong surface heating and dense urban fabric intersect. Its most prominent cluster is in the central eastern coastal industrial corridor, and has clusters further east and north. For a closer interpretation these localities have been grouped in three representative zones shown in figure 4.

The main quantitative ranges and decision rules followed in the study are summarized in Table 2. The thresholds are not intended to be health-based exposures. Instead, they deliver an operational definition of a "dense-built" hotspot defined by high LST within the selected summer composite which can be reproduced. This resulting map is especially appropriate for screening and prioritization, showing where

in the urban environment further field measurement should be performed, and adaptation options (material mapping) should be considered.

Table 2. Set of key analytical indicators, hotspot criteria

Indicator	Value / criterion	Interpretation
Study area	88.40 km ²	Central Baku analytical boundary
Landsat scenes	13	Filtered summer scenes used in composite
LST range	30.73–52.60 °C	Observed mapped land-surface range
Built-up density range	0–98.04%	GHSL built-surface fraction
High-LST criterion	≥45 °C	Thermal screening threshold
High-built criterion	≥70%	Dense built-surface threshold
Joint hotspot	Both criteria met	Priority overlap area

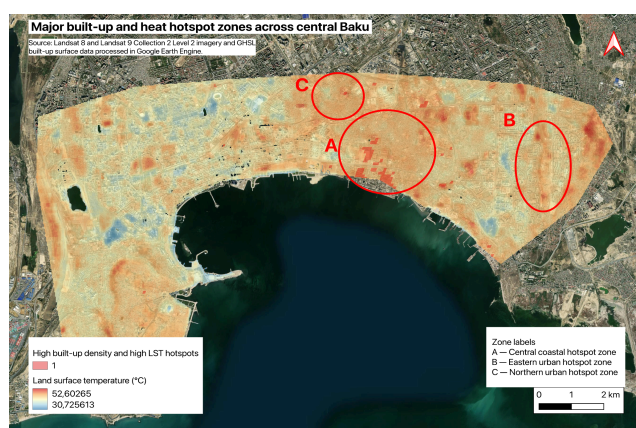


Figure 4. Major hotspot zones identified from the spatial overlap between high land surface temperature and high built-up density across central Baku.

The joint mask has a vast decrease at the spatial extent as compared to the LST and built-density layer individually. This selectivity is analytically useful, as it will map areas with two planning issues of concern. Warm surface, low BD, could be bare soil or construction site or other non-building surface, cool surface, high BD, could benefit from vegetation, cooler material or shade. In that mask, both cases are blurred and drives attention to regions where there is a prominent overlap between high density construction and high temperature.

The greatest amount is found in the centre/industrial coastal belt, which makes up the base of Zone A with smaller clusters to the east and north, and some individual pixels elsewhere. This pattern highlights a lack of the hotspot condition even in a highly-enveloped study area. The findings are in line with zone-based logic as presented by Ramos Zúñiga and Gomez Arredondo (2025) in their Analysis of Villahermosa, highlighting the unique nature of specific commercial and infrastructure areas within the broader urban thermal landscape.

Figure 4 also illustrates the necessity to read the hotspot mask in conjunction with the continuous background of LSTs. Information concerning gradients just outside of the threshold is eliminated, but the binary overlay communicates the priority status. Some warm orange regions are next to a red hotspot, and they may be only slightly different from the hotspot, and some cooler blue green regions are well-separated from the hotspot. Therefore, the threshold should be viewed as a screening boundary and not a physical one to be used in planning. The thermal context and the continuity of urban morphology should be taken into account in the intervention design.

The three selected areas include different morphological contexts and allow different levels of understanding about the

urbanisation-temperature relationship. The eastern urban/development fabric (Zone B) defines a compact area, while large impervious structures within a finer-grained northern fabric (Zone C) dominate the western portion of the area called Zone A. The same threshold situation thus comes up in different built form combinations. The main finding of this study is that the effect of urbanization on LST is apparent at spatial dimensions, and the mechanism is mediated by urban surfaces' types, scales and spatial configurations.

Zone A: central coastal hotspot

Zone A (Central Coastal Industrial corridor) is the industrial corridor that is the largest and most continuous joint-hotspot cluster. The detailed map in Figure 5 depicts a primarily built-up area with a number of large industrial land uses, storage and processing areas, extensive paved or compacted surfaces, significant roads, and not much continuous vegetation. The intersection between several red hotspot cells and a large roof or industrial parcel type is consistent, as well as with a large amount of paved logistics space. The hotspot appears continuous in space; they are not a result of one individual "roof" but of a more expansive "assembly of industrial surfaces."

To better account for the urban morphology some terms that are only present in Zone A are described below. Industrial sites can have the high built-surface fraction and large areas of exposed services, metal roofs or concrete built roofs, storage tanks, and internal roads and low vegetation. The materials are able to store high amount of solar energy and they have high values of their surface temperatures during the day time. The pattern is similar to that of industrial hotspots described in other urban analyses such as the industrial and commercial clusters in "hot zones" described by Ramos Zúñiga and Gomez Arredondo (2025), and the density-based patterns noted by Song et al. (2020).

Zone A exemplifies also the importance of the historical industrial geography of Baku. Both east and center coastal parts of Baku have long been home to oil-related developments and have been subject to extensive redevelopment. The thermal map thus reflects a hybrid urban landscape of legacy industrial sites, modernised energy infrastructure, transport corridors and new development. Planning-wise, the appropriate mitigation options are likely to be different from the options for a purely residential district. Reflective or cool roofing, shaded service areas, and planned tree placement (operationally practicable), with addition of permeable high-performance/replacement roofing and heat-savings development criteria may be more feasible than conventional park expansion within active industrial parcels.

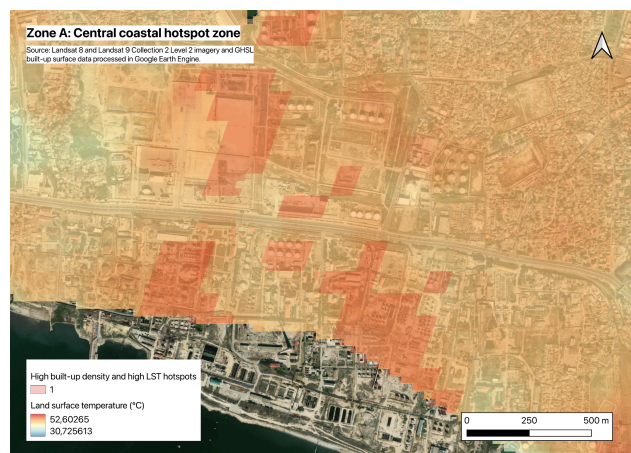


Figure 5. Detailed view of Zone A, the central coastal hotspot zone, showing the overlap of elevated LST and high built-up density.



Photograph A. Representative ground-level context for zone a industrial/refinery environment

Licensed source: Heydar Aliyev Baku Oil Refinery in 2025 by Aykhan Zayedzadeh is licensed under CC BY 4.0, Wikimedia Commons

Based on the detailed Zone A image, there are no restrictions on the hotspot and they can be setup on rooftops of buildings. The red cells are on top of a large industrial surface including a wide service road, storage/processing facilities, and wide exposed surfaces. Combined, these components decrease opportunities for evapotranspiration and enhance the body of heat holding material. Thus, the spatial continuity of the hotspot is likely to correspond to a landscape-level industrial hotspot, rather than to a specific structure. Not quite compact residence morphology; one of the reasons why a building-count interpretation would not be sufficient.

It is interesting to note the coastal location of Zone A: despite such proximity to Caspian, the high LST signal is not excluded. The map does not indicate if the sea-breeze circulation was occurring during each Landsat pass; however, the map indicates that it was not enough to overcome a warm surface pattern in the composite, as seen near the coast. Thus, surface properties of industrial surface and lack of vegetation are able to overwhelm local daytime LST even close to a large water body. This serves to emphasize the difference between temperature experienced on the ground from the coast due to potential atmospheric cooling and direct radiometric temperature of sunlit urban materials.

The zone is also a showcase of the environmental co-benefit opportunities of industrial modernization. Surface heating may be mitigated with strategies like high-albedo roofing and shaded parking and service areas, with a focus on providing tree belts where operationally viable, permeable or lighter paving, and site landscaping, which support the overarching goal of environmental-quality. These interventions should address industrial safety and water restrictions, and not be a literal adaptation of residential greening models. The remote sensing map is used to give the spatial information on where parcels should be detailed-engineered.

Satellite data, however, is not able to show all of the material properties; one ground-level photo of Zone A is quite important. Comparing with field imagery can confirm hotspot cells are valid in comparison to metal roofs, dark asphalt, concrete yard/shade areas, storage tanks or active construction. The photograph and its colored grid, supplied with Figure 5, is therefore not just decorative, but instead is meant as a standalone qualitative validation step between the thermal result based on the pixels and the real-world surface conditions.

Zone B: eastern urban hotspot

Going east, there is a contrasting zone (B) of urban hotspots. The high resolution map in Figure 6 illustrates a combination of large building footprints, some vegetation, bare areas and some open construction,

road imagery and very high rise residential construction. Although the hotspot is concentrated in less area than Zone A, it is part of a highly urbanized space in which various surfaces types are closely located. Considering this mixed morphology is important, since, even if the built surface fraction is not as high as in neighbouring residential blocks, ground originally devoid of buildings can reach high temperatures in summer, while very large roofs and parking area can amplify the thermal loading in the local level.

The eastern corridor thus shows that high temperature cannot simply be assumed to be due to a high building number. Urbanization is a combination of many aspects such as building development, urban roadway, parking, urban construction activity, reduction in evapotranspirative area and alteration of anthropogenic energy usage. Even if some of the neighbouring residential complexes have landscaping of courtyard or plants producing shade the local field of LST can be raised, if such a situation exists. Similarly, Fu and Weng (2016) highlighted that thermal signatures change with land-use/land-cover changes with multiple components, not one single component.

The thermal performance of large roofs and bare ground, continuity of street tree system and shading along pedestrian pathways, and timing of greening in construction and redevelopment should be key considerations for mitigation in Zone B. Heat exposure in the zone may be more directly linked with human activity while in operation each day due to the inclusion of dense residential functions in the zone. Detailed measurements in the future of air temperature, building energy demand and pedestrian heat stress would greatly aid the satellite based type of screening that has been proposed.



Figure 6. Detailed view of Zone B, the eastern urban hotspot zone, showing the overlap of elevated LST and high built-up density.



Photograph B. Representative ground-level context for zone b high-density residential and transport environment

Licensed sources: Hazi Aslanov settlement in Baku (from Interfase) (CC BY-SA 4.0), Wikimedia Commons

Zone B is a smaller more compact area than Zone A but the image does show a large built area, which is quite sharply contrasted to the surrounding residential fabric. The hotspot corresponds to extensive surfaces of built-up roofs, and large developed surface in an area of intensive construction and high accessibility of transport. The pattern indicates that thermal pressure may be identified in relatively modest development parcels when the surrounding neighborhood might not meet the same “joint threshold.”

The morphology of Zone B also shows the transitional and peculiar nature of the east part of Baku. Giant modern buildings, open areas for development and crowded residential blocks are all within a short distance of each other. Vegetative removal of vegetation and/or exposure of soil or building materials may raise the ambient temperature during the day period temporarily until vegetation has been successful and sustainable. Rapidly-changing areas (in the context of the GHSL density epoch) should be interpreted with caution: development that currently appears on imagery may not have been captured by the GHSL built-surface grid that was used for the 2024 composite.

The priorities for mitigation are different for residentially relevant hotspots than those for an industrial complex. Including trees along walking paths, street trees (where moisture can be provided), cool or green roofs, minimizing the area of dark-pavement, and providing shading at parking spaces can all do so directly as effects on thermal comfort and energy demand. These measures simultaneously overlap, and pertain, with considerations of green-economy goals, since they generate investable retrofit and public-realm projects. Sadiqov et al. (2026) also highlight the need for financing mechanisms for Azerbaijan's low carbon transition, and the same approach could be taken for urban heat adaptation.

Close-up map clearly illustrates the importance of scale. The hotspot can be associated with familiar building shapes, and roads at 150 m resolution, although at the citywide level, Zone B is represented as a small patch. Since implementation takes place at the level of streets, blocks and sites, this downscaling from the level of a metropolitan raster is vital. Another step that may help to determine if the hotspot is related to the roof material, paving in a yard, current construction, or other type of surface is the inclusion of a site photograph.

Zone C: northern urban hotspot

Zone C is in the north side of the study area, consisting of a high density mosaic of low rise domestic fabric, warehouses and industrial structures and significant transport infrastructure. The hotspot in Figure 7 is contained in several large rectangular buildings which are surrounded by a smaller polygonal urban fabric. The hotspot is smaller and more fragmented than Zone A and more discontinuous and complex than Zone B, where surrounding urban fabric is more mixed with the presence of more lowrise buildings and non-residential parcels.

All this morphology fits in the theory of “thermal hotspots”, which can develop where large impervious buildings are placed against highdensity urban neighbourhoods. The coarse GHSL grid also reflects the high built surface fraction and Landsat also characterizes the large thermal signature of roofs, paving surfaces and surrounding surfaces. This local configuration can therefore generate warm patches even in the absence of a very high level of impervious cover characteristic of Zone A elsewhere in the city. The effects of impervious-surface density and aggregation have been reported elsewhere in cities where spatial configuration of built surfaces can affect LST, in addition to the percentage cover (Estoque et al., 2017).

Zone C also applies to urbanization with relation to transport in Baku. There can be cumulative environmental pressures such as traffic, air pollutions, heat etc. which can be faced by major arterial corridors or mixed industrial-residential areas. The multi-hazard environmental screening would be beneficial use as suggested by Arifzade et al. (2026) in other industrial cities for the relation between transport and particulate pollution. Combining the existing LST and built-density layers with traffic intensity, exposure to PM2.5/PM10 and vulnerability-indicators layers may help to pinpoint regions in which multiple urban environmental impacts coincide.



Figure 7. Detailed view of Zone C, the northern urban hotspot zone, showing the overlap of elevated LST and high built-up density.



Photograph C. Urbanized streetscape along Heydar Aliyev Avenue in the northern urban hotspot zone of central Baku.

Source: Tərxan Paşazadə, own work, CC BY-SA 4.0.

However, Zone C is different from the previous two examples: the hotspot is part of a larger neighborhood, which is more diverse and comprises low rise structures. The image shows a scene with several large rectangular buildings standing among a web of smaller structures and what appears to be streets. Where the surrounding neighborhood is mixed in its thermal properties, the red overlay follows these larger impervious features, indicating that parcel scale and roof area can be determining factors. The pattern illustrates that a high-temperature hotspot is a product of a limited number of high-temperature surfaces, not necessarily a uniform high-temperature district.

Significant transport connections and mixed industrial-residential land use are also related to the northern site. These environment conditions may come with other environmental pressures. Zone C depicts the type of corridor where integrated monitoring would be useful; although there is no air-quality data analysed here, it was found that industrial and transport factors are part of the explanation of particulate pollution found in Sumgayit and Almaty by Arifzade et al. (2026). Future studies will be conducted to add traffic intensity and

PM measurements and population exposure to see if thermal and air-pollution burdens are spatially correlated.

Local heterogeneity is also highlighted in the cooler patch seen to the west/southwest of the main zone C hotspot. Those LST differences can be significantly large as vegetation, open space, surface moisture or shading vary, even within a very urbanized north part of the city. This observation is in line with the main conclusion that urbanisation is not thermally homogeneous. The built density gives the indication of the direction of the tendency of the structure, which only translates into a high-temperature surface at Landsat scale through the site-specific land-cover and morphological characteristics.

Planning recommendations are for interventions to be identified at the parcel level within Zone C instead of at a district level. Where appropriate, large roofs can be considered for reflective coatings, insulation or solar installations for heat mitigation; industrial yards can be considered to replace materials with shade and; transport corridors can include trees, shelters and lighter surfaces where appropriate. The ground photo of Zone C should reflect these physical conditions and aid to develop the interpretation for publication.

Urbanization, built-up density and the thermal structure of central Baku

The data presented in Figures 2–7, taken together indicate a clear spatial association between the intensity of urbanization in central Baku and its surface temperature during summer. Built up density is common across the study area, and the hottest surfaces are associated with high density urban fabric coupled with any of the following factors: industrial material, large roof surfaces, exposed hardscape surface or construction ground or transport infrastructure. The results confirm the differentiated interpretation of urbanization effect, thus. The likelihood of high LST being generated due to urbanization is significantly raised by the expansion of impervious surfaces and the corresponding decreases of evaporative cooling, while the amount of localized heating is conditioned by material properties, morphology, shade, vegetation, surface moisture and land-use function.

This is in line with the literature in general. Notably, Oke (1982) was dominant in emphasizing modifications to energy-storage and flux in cities, and Voogt and Oke (2003) highlighted the fact that surface expression of these are detected through thermal remote sensing, while Song et al. (2020) established that the impacts of building density operating on LST are influenced by climatic context. The thermal regime in central Baku, apparently, tends to magnify the effects of surface moisture and the lack of vegetation, while the legacy of the city's industrialization dictates the thermal aspects that are not characteristic of wholly residential cities. Qadimli and Mammadov (2026a) similarly conducted a study in Luanda, which concluded that projecting the correlation between the spatial nature of urban heat, urban expansion, and vegetation would be more suitable through the lens of a landscape mosaic than as a juxtaposition of urban and non-urban.

An example of this: the hotspot approach will help explain that a city-wide average would not be sufficient for planning purposes. A mean LST can however not differentiate the large industrial concentration in zone A, from the more compact mixed-use hotspot in zone B, or the urban-industrial hotspot “embedded” in zone C. These zones refer to different families of adaptation instruments. Different values and priorities might be applied to roof and pavement albedo, process-area shading and redevelopment standards for industrial areas; to street trees, courtyard greening, shade structures and energy efficient envelopes, for residential areas; coordinated

shading, surface-material and public-realm interventions, for transport corridors.

In all the three areas, the observations confirm the observed trend of relationships between built-up intensity and temperature with the expected direction of association, but not the one-on-one relationship between urban density and temperature. Despite the high built up density in the city, only a part of these cells will be affected by the thermal limits of 45 °C. Of course, there are some warm surfaces not located in the 70% built density parameter. The spatial intersection thus represents a combination that is more relevant to the title of the paper and the research objective. It pinpoints areas where urbanisation (dense built footprint) is associated with marked summer surface heating.

It is possible to state this distinction as necessary and sufficient conditions: The high built density is not required for all high-LST pixels nor is it required to ensure the maximum possible temperature. Dense construction can be cooler than bare construction, and bare surfaces can be hot if sunny and lacking vegetation, but also may be cooler if they are shaded, have surface vegetation or alternate surface character (color, morphology) that is cooler. However, the map shows a concentration of joint hotspots in industrial and large portion urban types signifying that high density and impervious urban development provide enhanced opportunities for surface heating effects. This subtle relation is in line with international literature and seems not to be overstated in terms of being a deterministic relationship (Estoque et al., 2017; Song et al., 2020).

The Baku case also illustrates the importance of disaggregating the notions of S-UHI and ITH for urban heat studies. One of the classical approaches in the determination of heat-island phenomena includes a reference point outside the urban area and measures an urban–rural difference. The question in the present study is: In an already urbanized central corridor, where are the built surfaces densest, and where do they overlap with high LST? This is more congruent with planning at block and corridor level as it considers the differences of urban environment instead of differences between Baku as a city and a rural reference.

This yields the spatial narrative which is compatible with other works in the remote-sensing of fast changing cities. Qadimli and Mammadov (2026a) indicated that combining the explanation of urban expansion and vegetation and heat could explain spatial environmental change in Luanda. While the present study in Baku more explicitly makes a separation of built density and the independent use of a settlement dataset, both studies reveal the role of urban form in shaping surface thermal conditions. This closeness is observed in the contrasting climatic settings indicating that the general relationship is stable, but the hotspot morphology is locally dependent.

Another implication is in the area of monitoring. As Landsat and GHSL are freely available, the workflow can be aptly repeated at frequent intervals without any major budget required to obtain data. An annual update to the summer LST composite (and built-density layer when GHSL updates will become available) may allow for a future monitoring program where planners can monitor hotspot areas as they expand or contract and/or shift after redevelopment. Satellite surface patterns combined with pedestrian-level air temperature and night-time cooling with field temperature sensors in Zones A to C would provide a much enhanced program.

Planning, green-economy and investment implications

The outcome has practical implications for promoting the greening of the urban landscape and the transition to a green economy. The concept of heat mitigation is many times discussed in a generic and

city-wide way, but the Baku maps highlight the need for spatial targeting. Investments should be planned to sites where the requirements of thermal pressure and the thickness of urban fabric are intertwined, and the land use functions delineate and calculate the potential size of interventions. A geospatial screening layer like Figure 4 can thus be used as an initial prioritisation tool for municipal greening policies as well as for cool roofing policies, shaded mobility planning and redevelopment needs.

But financing mechanisms are also relevant. Sadiqov et al. (2026) demonstrate the role of green-finance tools for low-carbon energy development in Azerbaijan. Green bonds, sustainability-linked lending, municipal climate funds or public – private redevelopment agreements may also be linked to urban heat adaptation if co-benefits like the reduction of cooling demand, outdoor comfort and reduction of heat exposure can be quantified. The most fundamental requirement is a baseline spatial map that makes interventions more transparent, priorities, and can then be evaluated.

NbS are still relevant and need to be tailored to the urban morphology and water scarcity. When strategically prioritizing interventions for ecosystem restoration as applied by Qadimli and Mammadov (2026b) through a spatial approach, remote-sensing-derived indicators can serve as a valuable basis for intervention prioritization. The same reasoning might be used to determine some blocks in central Baku with the potential to offer the most cooling benefit from tree canopy, pocket parks, shaded pedestrian corridors, or green roofs. However, on industrial or infrastructure locations, vegetation may require engineering solutions as well. As a consequence, a combination of NbS and material-based measures in a balanced way is more adequate than only one of them.

Finally, an integrated planning is needed for the coastal setting of Baku. There must not be separate coastal redevelopment, industrial modernisation, transport investment and urban greening agendas. In a coastal metropolis, heat resilience and water management/land redevelopment have interaction, as pointed out by Qadimli et al. (2026) regarding Azerbaijan's Caspian and inland water systems and their wider economic exposure. Surface temperature should thus be taken into view in urban adaptation strategies along with stormwater, water availability, air quality and the economic value coastal infrastructure.

The hotspot maps can be used in a layered approach of investing. At the initial level, remote sensing is used to pinpoint high surface temperature and built up areas that are recurrent. Local audits assess ownership, land use, roof material, shade, vegetation, and energy usage and vulnerable groups at the second tier. On the third level, projects are aligned with financing instruments, and measurable parameters. This sequence limits distribution of heat-mitigation resources to uniform citywide distribution, without regard to need, and links geospatial evidence to project-based decision making.

Site improvements that can improve energy efficiency, worker comfort and help reduce heat storage are also, possibly, capital intensive and may be required for Industrial Zone A. Zone B could be more appropriate to developer commitments, green-building codes, public space providing shade, residential retrofit programs. The interventions in zone C can be achieved with a combination of measures including industrial roof measures, greening of corridors, and public realm interventions and additions specifically catered to transport. To be able to distinguish among the different types of interventions is a direct gain of the zone approach. It translates a continuous image of a raster, into a collection of locally targeted planning questions not only a generic 'increase green space.

Thermal benefits could be integrated in the project appraisal and green finance could provide a supporting role. Sadiqov et al. (2026) demonstrate how energy investments in Azerbaijan can be green-financed. Examples of potential urban heat eligible expenditure items include; cool roofs, energy-efficient building envelopes, shade structures, solar-plus-cool-roof, planting trees (using conservative irrigation systems), and permeable surfaces and heat-resistant transit stops. For these projects to be financeable, municipalities and developers need baseline indicators and post-intervention monitoring. Initial layers for LST and Built-density are created here and could be combined with air-temperature, energy and social data.

NbS solutions have the value but need to be created for a water-constrained environment like Baku. According to Qadimli and Mammadov (2026b), the priorities are (1) spatial prioritization and (2) financing needs for ecosystem restoration in the Shahdag National Park. The same prioritization can be applied to vegetated courtyards and green corridors, and to tree canopy and pocket parks in an urban context. Species selection, irrigation requirement, soil volume and maintenance cost are however very important. Remotely sensed data may help to target the locations of cooling interventions and locally assessed ecological and engineering data may help to target the interventions that are able to be sustained.

It has a strategic planning element by taking into account the coastal context. Economic exposure related to Azerbaijan's strategic inland water systems and Caspian Sea is documented by Qadimli et al. (2026). The waterfront of Baku can function at the same time as an environmental interface, a transport corridor, a redevelopment area, and public space. Accordingly, heat sensitive coastal planning should be a part of an overall resilience strategy instead of being a standalone urban-design concern. Reflective materials, tree canopy, shaded pedestrian networks, and ventilation corridors are features that can be integrated into the construction of large redevelopment projects, and is more cost-effective than retrofitting after construction.

Finally, the results recommend integrating with the heat and other urban environmental indicators. Potential air-pollution, noise and mobility burdens can result on the same industrial and transport corridors, which are thermally stressed. Arifzade et al. (2026) gives evidence on the environmental importance of transport and industrial factors in the case of particulate matter (PM). It is possible to create multi-hazard urban environmental index for Baku, holding in account LST, PM_{2.5}/PM₁₀, traffic density, accessibility of green-spaces, socioeconomic vulnerability. Together, such an index would offer a more solid foundation for promoting equality in climate-resilient investing, compared with using temperature alone.

Limitations and future research

The findings from the present results should be considered a cross-sectional remote-sensing evaluation. The study does not aim at obtaining a building to built-up density causal coefficient in this case because it is mostly spatial overlay and hotspot screening rather than regression analysis. The sense in which the word "influence" is used in the title thus refers to the environment at a location; a spatial influence and association, rather than the experimental cause and effect sense of the word. One next step would be to randomly select pairs of LST and built-density values for the study area, and to approximate some linear, nonlinear or spatial regression models that controlled for vegetation, bare soil, proximity to the coastline and altitude.

The time constraint is also crucial. The observed GHSL epoch in 2020 is used to reflect the Built-up density and LST is summarized for summer 2024. This is suitable for a morphological assessment that can be performed for a near contemporary situation but is inappropriate

when measuring the urbanization change between these years. A multitemporal extension with specific GHSL epochs, Landsat archives, and construction statistics for each year would enable test to be carried out to see if the increase in built density has been accompanied by systematic changes in LST. In addition, field air-temperature loggers and mobile transects would facilitate linking satellite surface temperatures to the human thermal exposure.

The interpretations given for the three zones are based upon satellite and basemap data only, and should be verified with the field photographs and site observations prior to final publication. Areas A, B and C should be photographed on the ground; it is necessary that in these case study locations the dominant surface materials, building forms, road conditions and vegetation context be documented in real pictures. Therefore, the manuscript contains marked areal photographs place holders, with recommended “open license” sources of images that should be updated with ground photographs from the field or licensed images of the area for the version to be submitted.

There are a few issues to be noted when assessing the significance of any observed spatial association: First, Pearson/Spearman/regression coefficients are not calculated for the relationship between the two raster variables. The visual and threshold analysis is deliberately exploratory. Future pixel- and/or grid-level statistical model should resample datasets to a common analytical unit, and incorporate additional controls including NDVI, albedo, elevation, distance to coast, building height and land use class. Also consider spatial auto-correlation as neighbouring pixels are not independent.

Secondly, the 100 m GHSL grid and 30 m Landsat thermal grid have different spatial supports. Repeated sampling of the same layer to another layer can give an impression of accuracy but the present study is based on an interpretation of the clusters. Built density could also be combined with the other variable to a common grid (100 m or 250 m) and zonal statistics generated, thus allowing a formal relationship between mean LST and built density to be developed. This aggregation would also simplify the spatial fusion of population and socioeconomic data, and minimise sensitivity to the alignment of pixels.

Third, diurnal thermal dynamics may not be represented by a summer median. Surface urban heat islands can also vary strongly diurnally and there can be modification of the timing of the heat release due to coastal circulation. Alternatively, observations from MODIS or ECOSTRESS data could be incorporated into the analysis with local meteorological data, thereby extending the analysis to other times of day. The field location sensors in the three hotspot zones and selected cooler comparison locations would be particularly useful in identifying high daytime LST and associated high air temperature at night and low cooling.

Fourth, this analysis is performed with one present summer. The spatial pattern for 2024 should not be assumed for other years because of interannual variability in meteorology. If the same workflow was repeated for several years, it would indicate if the zones found were persistently hot in subsequent summers. An extension can be done in the temporal domain as well, with the potential comparison between built-up change and LST change, which will be more direct assessment of urbanization effects. This sort of time-series analysis is useful in studying thermal changes as a result of urbanization as shown by Fu and Weng (2016).

Fifthly, detailed morphological interpretations will require field photography and visits to the site for confirmation. Roof material and condition, road surface type and development patterns are easily observed using high-resolution imagery but may not be consistently

discernible from these images. Three of the positions for the photographs in the manuscript should therefore be substituted with georeferenced ground photographs from Zone A, B and C prior to final submission. The photographs are to be considered as qualitative validation, and should be dated and have their approximate (including date, coordinate and photographer/source) location indicated in the caption or, if these are unavailable, in the supplementary material.

However, the analytical design has remained helpful as a screening design in spite of these limitations. It uses freely available data, clear thresholds, and widely used software tools to enable the workflow to be easily replicated in other Azerbaijani cities. Thermal surface alone, built-density layer alone and detail hotspot interpretation together is more informative compared to LST alone and built-density layer alone. This also serves as a practical link between remote-sensing analysis and place-specific urban planning, the key applied focus of the research.

CONCLUSIONS

This work evaluated the spatial impact on the LST of the urbanization and BUD within an 88.40 km² central Baku study area. The analysis using the June by August 2024 Collection 2 Landsat 8 and Landsat 9 LST products gave a median summer LST surface from ~30.73 to 52.60 °C, and built-up density based on the 2020 GHS-BUILT-S product R2023A was between 0 and 98.04%. The two layers were overlaid using an operational hotspot rule which was based on LST > 45 °C and built-up density > 70%.

The spatial pattern that result demonstrates that high surface temperature is very much linked to high built up density, but the association is far from consistent. The biggest hotspot (zone A) is in the central coastal industrial zone, where large storage and processing facilities, paved surfaces and large roofs support a large heat-retaining surface system. Zone B also illustrates a more geographically concentrated area of possible eastern hotspots within a combining residential/commercial/development context, and Zone C demonstrates effective hotspot localized creation within diverse urban fabrics dominated by major impervious buildings within a northern neighborhood. Such differences help to validate the use of built-up density in conjunction with land-use function, surface material, vegetation, shade and urban morphology.

In methodological aspects, this study provides a workflow that is replicable and uses Landsat thermal products, GHSL built-surface data, Google Earth Engine and QGIS. The workflow can be adapted to other data such as vegetation indices, Building-height data, traffic, as well as air pollution and population vulnerability, and can be adapted for the rapid urban heat screening in data-constrained applications. The results facilitate targeted, low one-size-fits-all heat mitigation—different industrial hotspots will need different mitigations; as do dense residential and transport corridors. The maps serve as an underpinning for spatial priority setting of investments of cool materials, urban greening and other measures for climate-resilient mobility system redevelopment for the green economy.

Principal limitations are the cross-section design, the fact that the two datasets (built-up and thermal) were observed in different years and the lack of air-temperature measurements on site.

AUTHOR CONTRIBUTIONS

Conceptualization, N.Q. and U.M.; methodology, E.A. and N.G.; Google Earth Engine processing and GIS analysis, U.M.; validation and interpretation, N.Q. and U.M.; writing—original draft, U.M.; writing—review and editing, N.Q. and U.M.; supervision, N.Q. All

authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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DATA AVAILABILITY

The primary satellite and built-up datasets used in this study are openly available from the U.S. Geological Survey Landsat archive and the European Commission Joint Research Centre Global Human Settlement Layer. The Google Earth Engine processing logic and derived cartographic outputs are available from the corresponding author upon reasonable request.

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Mineralogical characterisation and techno-economic prospects of the Aydag deposit natural zeolite, Azerbaijan

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Keywords

Aydag deposit, Azerbaijan, clinoptilolite, natural zeolite, techno-economic screening

ABSTRACT

The mineralization of the Aydag deposit, situated in the Tovuz district in the Western part of Azerbaijan, is one of the most well studied occurrences of natural clinoptilolite in the South Caucasus, but its industrial potential is dispersed in mineralogical, process-performance and market distribution studies. The paper presents a pre-feasibility techno-economic screening, combining published mineralogical results, gas purification, catalysis experiments that were conducted on the Aydags, up-to-date natural-zeolites market statistics and adsorption and hydroponic comparative results. The average X-ray content of clinoptilolite in the samples published in the literature ranges from about 70–80%, and the CIS resource synthesis reports 55–65%, material heterogeneity has been confirmed which is why it is necessary to have a grade control based on domains. Field experience in the use of Aydag zeolite in dehydration of gas to low dew points has proven that this zeolite retains acceptable adsorbent capacity after 46 months of operation and is referenced in the literature to adsorbent-cost range of USD 120-230/t compared with USD 2,500-4,000/t for synthetic NaA. The study recently published by Azerbaijani researchers also shows that Aydag zeolite is a heterogeneous catalyst for transesterification of grape-seed-oil. However, many of the resource estimates have been published in the last number of years, with recent official and technical sources showing 20-25 Mt, and historical sources estimating 100 Mt, making this impossible to value as a bankable resource. Based on the evidence, a staged development strategy is applicable, starting with gas treatment, water-treatment media and catalyst-grade products and moving on to agricultural and/or hydroponic validation.

INTRODUCTION

Natural zeolites are hydrated crystalline aluminosilicates, the permanent negative charge of which is created within the structure by the substitution of Al in the silica atoms and is compensated by exchangeable alkali and alkaline-earth cations. Their interpenetrated systems of micropores enable their application as materials for ion-exchange, adsorption, molecular-sieving, dehydration and catalysis (Kordala & Wyszowski, 2024, Velarde et al., 2023). Clinoptilolite is particularly significant among the natural zeolites due to its relatively high silica content, its chemical stability, its cation selectivity, and its plentiful occurrence in geology. The properties enable the inclusion of low cost mineral processing routes, generally in terms of simple selective quarrying, crushing, drying, sizing, washing and the eventual requirement for activation or surface modification, to produce products for multiple end-use markets (de Magalhães et al., 2022).

There are several zeolite occurrences (volcanic or volcanic gen sedan-tary) in Azerbaijan, where the natural zeolite resource of clinoptilolite is the best known Aydag deposit near Tovuz known to date. A large clinoptilolite-bearing body in the Lesser Caucasus was analysed by the optical, electron-microscopic, chemical, X-ray, thermal, and infrared methods (Kashkai & Babaev, 1976). The latest geological synthesis suggests that Aydag is a part of the Gazakh trough, and the productive horizon – zeolitized Upper Cretaceous

vitreous-ash tuffs are the result of hydrothermal-epigenetic alteration of volcanic glass (Rasulova et al., 2017). Similarly, Karimov (2026) highlights the genetic influence of parent pyroclastic rock and the tectono-magmatic environment of mineralization of clinoptilolite and mordenite of Azerbaijan.

Yet, there are three issues that have not been resolved and with this significant amount of knowledge a straightforward investment interpretation has been hindered. One is the difference in estimation of the clinoptilolite content based on the scale of the samples and the basis of analysis. Second, discrepancies exist in published estimates of tonnage: about 25 Mt, according to Belousov et al. (2024); 100 Mt, according to Mustafayeva (2008) – historical industry reporting – and 20 Mt, according to the official Azerbaijan portal. Third, the best application data is spread out among various application areas – such as drying the gas and catalytic applications – Aydag specific data exists for drying the gas and using clinoptilolite in the catalysis, many data on water-treatment and agricultural application are from other clinoptilolite deposits. Their evidence classes would be treated related to each other and this would be an overstatement of technical readiness.

Therefore, this study goes on to (i) bring together the mineralogic and chemical character of the Aydag natural zeolite, (ii) separate mineralogic and/or chemical performance evidence specific to Aydag as compared against other transferable clinoptilolite zeolites, (iii)

screen industrial paths using technical and market indicators in the literature, and (iv) elicit information essential prior to a full techno-economic assessment, mining plan, or investment decision. As such, the study is not a new reserve estimate, nor a laboratory characterization campaign, and in fact is a mineralogical "secondary data" synthesis and pre-feasibility screening.

LITERATURE REVIEW

The value of Clinoptilolite is based on the tetrahedral aluminosilicate framework and it contains exchangeable Na⁺, K⁺, Ca²⁺ and Mg²⁺ ions. The performance of natural-zeolites, however, is highly deposit-dependent, which is due to their variable framework composition, associated clay and silica phases, surface area, (naturally-occurring) cations and weathering history are geographically different (Velarde et al., 2023). Such dependency on the deposit is especially significant for techno-economic analysis as two products under the same name "clinoptilolite" may have different adsorption capacity, abrasion resistance, activation response, and yield of beneficiated product.

Among the best-established higher value applications, water and wastewater treatment stand out. De Magalhães et al. (2022) explain on a review about the extraction of nitrogen species, phosphorus, metals, dyes and organic compounds using a mixture of adsorption and ion exchange processes using zeolite-based treatment. For natural clinoptilolite, Dosa et al. (2022) achieved a 98% removal percentage of methylene blue at 100 ppm in 15 min and reported that the competition of adsorption process can decrease the elimination percentage of the cations in multi-contaminant systems. This can be extended by modified clinoptilolite that increases the spectrum of contaminants that can be accessed. For instance, manganese dioxide (MnO₂) modified version greatly enhances arsenic affinity as compared to raw clinoptilolite (Camacho et al., 2011) and acid modification can be achieved for cadmium and lead removal from refinery effluents (Aghel et al., 2020). In controlled experiments it was shown that the removal value of Ni was 87% and Cu, Cd, and Pb were 99–100% after the activation of Shankanay clinoptilolite at 550 °C (Kuldeyev et al., 2023). These results show process potential that is not too be understood with the Aydag because the mineralogical differences impact the uptake and it can not be numerically transferred to Aydag without validation.

The subject of gas purification is very topical for Azerbaijan since there is direct evidence on it from Aydag. Alekberov et al. 2021 reported that natural Aydag zeolite is favorable in terms of the activity to gas purification and drying, has good crushing activity and a long service life than synthetic zeolite. Aliyev and Sardarova (2023) made a technical-economic synthesis, where the cost of the natural Aydag material was found to be USD 120–230/t, and the synthetic NaA was USD 2500-4000/t. The values used below are source-specific and for a specific date, however, they offer scarce techno-economic evidence of the connection of the Aydag mineral to an industrial operation that occurs in practice.

Agricultural and controlled-environment applications provide a value proposition to water retention, cation buffering, and nutrient management instead of contaminant capturing. A study conducted by Doszhanov et al. (2026) assessed the use of natural Shankhanai zeolite in NFC hydroponics for *Medicago sativa* and *Lactuca sativa*, with Arifzade as co-author. The zeolite exhibited 21.80 m²/g before cultivation and 16.66 m²/g after, which is significantly different from 0.49 m²/g for the foamed-glass control, and it resulted in better seedling viability and root structure (Doszhanov et al., 2026). This is significant as it represented a landmark to the existence of a market for

value-added zeolite products, and is an experimental substrate from Kazakhstan, not Aydag; the actual generation of a hydroponic product from Aydag is thus a possibility that can be tested but has yet to be established.

The range of potential products is further extended through the use of catalytic applications. Mukhtarova and Suleymanova (2026) conducted transesterification of grape-seed oil in the presence of natural Aydag zeolite as the heterogeneous catalyst and found the maximum yield of fatty-acid methyl esters 92.9 wt. % at 120 min and 65 °C. The direct use of Aydag material is of economic interest because the higher the value of the unit of material utilized, the more worthwhile the use is, if the other economic factors (catalyst reusability, deactivation, regeneration energy, scale up performance) can be accounted for explicitly.

It would also be useful to consider the future prospect of Aydag zeolite development under the general umbrella of the environment management and the green-economy transition. Recent studies have shown that environmental pressures induced by human activities such as industrial and transportation can be quantifiable via particulate pollution, underscoring the need for environmentally-friendly materials and technologies that can aid pollution mitigation and environmental remedial efforts (Arifzade et al., 2026). Meanwhile, the processes of land-cover alteration, vegetation change, and surface-temperature dynamics within rapidly urbanizing areas serve as an example to show the growing importance of the need for integrated approaches in resource and environmental management (Qadimli & Mammadov, 2026). Such transition can occur not only by adsorption and industrial purification but also in valuable crop cultivation including the use of natural zeolites as substrates in the cultivation of crops in controlled hydroponic systems, which have shown a positive functional performance (Doszhanov et al., 2026). Economically, foreseeing the future commercialisation and technological upgrading of domestic mineral resources could be further enhanced by utilising green-finance mechanisms that are able to mobilise investment for environmentally sustainable technologies and infrastructure – as seen in the country's renewable energy sector recently (Sadiqov et al., 2026).

MATERIALS AND METHODS

Research design. A structured secondary-data synthesis is used. The evidence was divided into four categories: (1) Evidence related to the mineralogy and geology of Aydag; (2) Evidence related to the process performance in Aydag; (3) Evidence related to performances of analogous applications of clinoptilolite in other deposits; and (4) Evidence related to market/ resource context. This hierarchy was established to avoid analogue results being reported as Aydag properties measured.

Mineralogical data. Deposition was rebuilt based on the classic mineralogical study by Kashkai and Babaev (1976), the Azerbaijan-wide synthesis conducted by Karimov (2026), the study by Rasulova et al. (2017) for the Gazakh-trough and the resource review of the countries of CIS by Belousov et al. (2024). The mean major-oxide values of Figure 1 are based on the eight clinoptilolite-tuff analyses reproduced from Rasulova et al. (2017, Table 1). No new XRD, XRF, SEM, BET, thermal or cation exchange measurements were required to create this paper.

Resource screening. Tonnage estimates have been used in lieu of reconciled reserves as reported-source values. The official Azerbaijan portal value of 20 Mt is qualitatively compared to the almost 25 Mt inferred from Belousov et al. (2024) and the historic figure that Mustafayeva (2008) has reported of 100 Mt. The lack of consistency

in the aforementioned parameters across these sources meant that it was not possible to attempt to carry out a present value calculation based on in situ tonnage.

Techno-economic screening. Direct Aydag performance indicators were excised from the Alekberov et al., (2021) article while the comparative ranges of costs were taken from Aliyev and Sardarova (2023). The midpoints were calculated using ranges provided for the various sources: synthetic NaA midpoint = $(2,500 + 4,000)/2 = \text{USD } 3,250/\text{t}$; Aydag midpoint = $(120 + 230)/2 = \text{USD } 175/\text{t}$, therefore reported midpoint ratio would be approximately 18.6. This ratio is a description of cited literature, comparison and not a quotation for the market 2026. Market context has been obtained from U.S. Geological Survey Mineral Commodity Summaries 2026, a publication that provides details on the production and use categories for natural-zeolite, and recent trends in the unit values of U.S. mineral products (U.S. Geological Survey, 2026).

Application-readiness assessment. Qualitative discrete scores of direct evidence, transferable benchmark and research-stage prospect were assigned to each pathway. Direct evidence needed to be the experiment or industrial process to have been expressly employing Aydag material. Transferable benchmarks were added only to be able to identify possible directions or products in processing. In deliberate fashion, the study does not provide an NPV calculation, an IRR calculation, a payback period or a mine-life calculation because public available data on the characteristics of the mine, its production schedule, the recovery in the beneficiation process, the capital costs, the operating costs, the product specification yield, and a binding off-take price are unavailable.

RESULTS AND DISCUSSION

Monazite occurs in various rock types

Aydag is located in the Tovuz district in the Gazakh trough of the Lesser Caucasus at a distance of 7 km from the city of Tovuz (Rasulova et al., 2017). Zeolitized ash tuffs prevail in Upper Cretaceous (K) volcanic-sedimentary successions in the productive unit. The high silica zeolitites are considered by Rasulova et al. (2017) to be hydrothermal-epigenetic products created as a result of the uplift of the rocks and the main precursor being the volcanic glass of acidic to intermediate and locally basic composition. The resulting rocks are not necessarily mineralogically homogenous – clinoptilolite is predominant, but heulandite, mordenite and non-zeolitic phases may occur. This heterogeneity is significant because, a flow of a bulk quarry product is not the same as a flow of a beneficiated clinoptilolite concentrate as economy demonstrates.

The most commonly mentioned Aydag grade numbers do not correspond directly. According to Rasulova et al. (2017) the average clinoptilolite content is on the order of 70-80% based on X-ray diffractometry and mineralogical analysis, and local variation occurs in zeolite content between channels and drill intersections. In a wider comparison in the CIS region, Belousov et al., (2024) write about 55-65% Clinoptilolite for Aydag. Historical industry reporting refers to 50–59% in the sense of early Soviet exploring (Mustafayeva, 2008). These values are not intended to be individual “true” grades, but rather reflect grade heterogeneity within a given scale (and which has been driven by a mix of different ore domains, sampling campaigns and analytical protocols). So a commercial project would not be able to use one deposit wide average figure, as opposed to a geometallurgical domaining.

Chemical composition (silica rich). The average of eight analyses of the Aydag/Gazakh-trough clinoptilolite-tuffs reproduced by Rasulova et al. (2017) is summarized in figure 1. SiO₂ is predominant, Al₂O₃

the second principal framework oxide and CaO the principal alkaline-earth oxide of the plotted oxide series. The composition is typical of a high silica clinoptilolite system, and is compatible with the cation exchange and thermal dehydration activities anticipated of natural zeolite. The predominant geological and mineralogical indicators are summed in table 1.

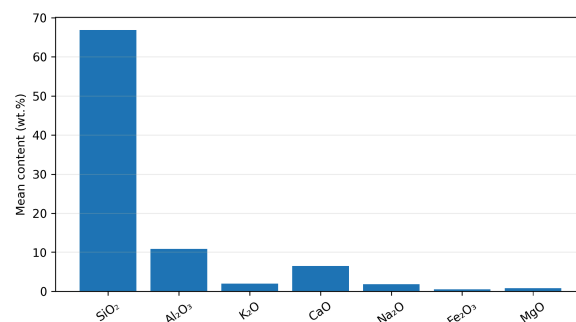


Figure 1. Average major-oxide composition of Aydag clinoptilolite tuffs.

Note: Author calculation from eight analyses reproduced in Rasulova et al. (2017, Table 1). Values are analytical averages and do not constitute a modern resource-grade estimate.

Table 1. Consolidated mineralogical and geological indicators for the Aydag deposit

Indicator	Published evidence
Location	Tovuz district; approximately 7 km from Tovuz city.
Host/material	Upper Cretaceous zeolitized ash tuffs and volcanogenic-sedimentary rocks.
Genetic interpretation	Hydrothermal-epigenetic alteration of volcanic glass.
Dominant zeolite	Clinoptilolite; heulandite and locally mordenite/other phases reported.
Clinoptilolite content	~70–80% in average samples (Rasulova et al., 2017); ~55–65% in CIS resource synthesis (Belousov et al., 2024).
Rock porosity	Around 15–20% or more in the 2017 study.
Industrial implication	Selective mining, grade control and product-specific beneficiation are required because the productive stratum is non-uniform.

Uncertainties as to resource base and valuation consequences

A large resource base exists but it has not yet been formalized to become bankable. According to the official Azerbaijan information portal, the prospective reserves of Aydag tuffs are 20 Mt; there are approximately 25 Mt according to the CIS mineral-resource synthesis by Belousov et al. (2024). A 2008 article in the industry, however, took up an old Soviet story and mentioned 100 Mt (Mustafayeva, 2008). The historical summaries have also continued to state figures such as “over 100 million tonnes.” However, the figure reported in the present paper was not accepted as a proven or probable reserve due to the materially lower figure as reported in the newer official and technical sources.

This mismatch results in a direct techno-economic impact. However, this in-situ tonnage multiplied by a market price would be got up to create a false “deposit value” since the market prices are for the processed product and not for in-situ tuff that is heterogeneous in nature. The current resource model, measured densities, product yield testwork, NFR mineralization due to mining dilution, recoveries, moisture, particle-size specifications, and waste ratio, processing costs and marketable-grade distribution are needed to defensibly value the resource. However, the range 20–25 Mt is only proposed here as a

historical conservative published screening envelope until these data will be available, and 100 Mt as a historical figure that should be itself revalidated. Source discrepancy and interpretation utilized in this screening is summarized in Table 2.

Table 2. Published Aydag tonnage estimates and interpretive status

Source	Reported figure / status
Republic of Azerbaijan portal (n.d.)	20 Mt prospective tuff reserves; official public-information value.
Belousov et al. (2024)	~25 Mt; recent technical synthesis for Russia/CIS zeolite resources.
Mustafayeva (2008)	100 Mt; historical industry/media reporting based on earlier exploration narrative.
Interpretation used here	20–25 Mt is the conservative screening range; 100 Mt is not treated as a current bankable reserve.

Direct gas-purification performance and cost evidence

Gas treatment is the strongest near-term industrial case because the evidence is directly Aydag-specific. Alekberov et al. (2021) evaluated natural Aydag zeolite in gas purification and dehydration, including comparison with synthetic zeolites. Their industrial results show fresh Aydag adsorbent moisture capacity of about 8–9 wt.% and hydrocarbon adsorption of 1.7–2.1 wt.%. After 46 months of operation, moisture capacity remained 7.2–7.5 wt.% and hydrocarbon capacity 1.5–1.8 wt.%, indicating that useful performance was retained over multi-year service. The same study reported natural-zeolite gas dew points in the vicinity of –40 to –45 °C under tested conditions and described sulfur-compound activity close to synthetic CaA for the Aydag material.

The direct cost comparison is particularly striking but must be interpreted cautiously. The literature reports a conditional cost of USD 120–230/t for Aydag natural zeolite and USD 2,500–4,000/t for synthetic NaA, together with service life of more than 3.5 years versus 2 years for NaA. Midpoint comparison gives approximately USD 175/t versus USD 3,250/t, or an 18.6-fold difference. Table 3 summarizes the source-specific gas-drying comparison. This is not a current market quote, and a present-day project would need to include quarrying, crushing, drying, granulation, transport, regeneration energy, disposal, and quality-control costs. Even so, the combination of lower reported adsorbent cost, greater crushing strength and longer service life gives Aydag a credible substitution rationale where process specifications can be met. Figure 2 visualizes the reported cost ranges on a logarithmic scale.

Table 3. Source-specific techno-economic comparison for gas drying

Metric	Synthetic NaA	Natural Aydag
Moisture adsorption	14–16 wt.%	8–9 wt.%
Hydrocarbon adsorption	2.5–2.7 wt.%	1.7–2.0 wt.%
Crushing strength	0.55 kgf/cm ²	0.65 kgf/cm ²
Service life	2 years	>3.5 years
Conditional cost	USD 2,500–4,000/t	USD 120–230/t

Note: Table 3 compiles technical indicators from Alekberov et al. (2021) and the conditional cost comparison reported by Aliyev and Sardarova (2023). All values should be treated as source-specific technical/economic indicators rather than current supplier quotations.

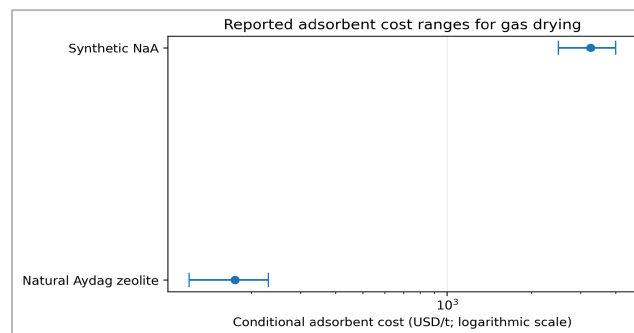


Figure 2. Reported conditional adsorbent-cost ranges for gas drying.

Note: Literature-reported cost ranges from Aliyev and Sardarova (2023); not adjusted for inflation, logistics, processing or present-day product specifications.

Potential water treatment and environmental-remediation applications

The mineralogical signature of Aydag is suitable for water-treatment; however, datasets of modern Aydag adsorption are much weaker than the evidence of gas-treatment. Most likely mechanism for cationic pollutants is ion exchange which is facilitated by exchangeable alkali/alkaline earth cations and the negatively charged framework. In all natural-zeolite reviews, the use of clinoptilolite is consistently cited as one of the most popular natural zeolites for use in heavy metal adsorption, with a caveat that its capacity depends on chemistry of the deposit and the pretreatment (Velarde et al., 2023).

Potential performance envelope (analogous experimental benchmarks). In the context of methylene-blue removal treatment, dosa et al., (2022) found natural clinoptilolite removed 98% methylene blue, of a solution of 100 ppm, in 15 min; and a price range of natural clinoptilolites of the order of USD 200–600/t. Gidayanova et al. (2002) have demonstrated that the heavy-metal-capture efficiency can be significantly increased by acting at elevated temperatures (550 °C), as was used by Kuldeyev et al. (2023) with Shankanay-zeolite (87% Ni, 99% Cu, 99% Cd and 100% Pb). Those benchmark removal efficiencies are visualised in Figure 3. Further modification of clinoptilolite with acid for Pb/Cd and with MnO₂ for arsenic can further tailor the clinoptilolite (Aghel et al., 2020; Camacho et al., 2011). These data support the use of Aydag for pilot testing, but without side-by-side experiments, they do not support the claim of similar removal efficiencies for Aydag.

In order to commercialization, contaminant-specific qualification of Aydag water-treatment media should therefore be made. The required tests comprise of cation exchange capacity, BET area, pore-size distribution, leachable elements, particle attrition, hydraulic head loss, breakthrough curves, regeneration efficiency, spent-media classification and performance under competing ions. If the raw mineral is too cheap to be chemically activated, too finely ground, or will require significant washing or disposal costs, it may not have an economic edge over the other media; on the other hand, granular media that will need repeated regeneration can allow the creation of a huge lifecycle cost advantage.

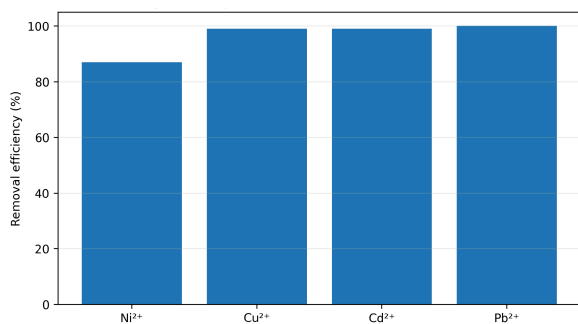


Figure 3. Analogous natural-clinoptilolite heavy-metal removal after 550 °C activation.

Note: Benchmark data from Kuldeyev et al. (2023), Shankanay deposit, Kazakhstan. These values are not Aydag measurements and are presented only as a process-development benchmark.

Commissioning consultancy for agriculture and hydroponics and controlled environment products.

Natural zeolites are also utilized in large quantity agriculture markets in the applications of soil conditioners, nutrient carriers and mineral applications for feeds. According to the USGS data, animal feed is the leading category of natural zeolite sales in the United States, with 42% of the total tonnage in 2025, and odor control is the next largest category, at 15%. Water-related and soil-related uses also are significant. (U.S. Geological Survey, 2026). In Aydag, these markets could be able to absorb lower cost size fractions not suitable for premium adsorbents and catalysts, thus increase quarry yield and decrease waste.

The sought after 2026 Plants paper was designed to offer a connecting thread for controlled environment agriculture from current scientific practices. Doszhanov et al., (2026) compared BET surface area of Shankhanai natural zeolite with the foamed-glass substrate in a hydroponics system reported the BET surface area of fresh zeolite as 21.80 m²/g, which dropped down to 16.66 m²/g after cultivation and 0.49 m²/g for foamed glass substrate (control). The zeolite favorably affected the viability of seedlings—cultivating of *M. sativa* root system showed more branches—and also the morphological and metabolic response of *L. sativa* which was dependent on the substrate. The contrast of surface area is summarised in Figure 4. The relevance to Aydag is functional, but not direct: The study establishes the fact that a natural clinoptilolite-bearing substrate can produce a water- and nutrient-buffering substrate, but not that the quality of Aydag per se would be agronomically safe, saline, and result for crop response.

Having possible marketable amounts of products in different grades—bulk soil amendment, fertilizer carrier, controlled release nutrient blend and more higher specification hydroponic substrate. Different particle-size distribution is needed as well as dust control, washing and pH/EC control and certification. An economic benefit of a mine-to-market portfolio is that coarse, medium and fine fractions can be allocated to different products, rather than dealing with one commodity.

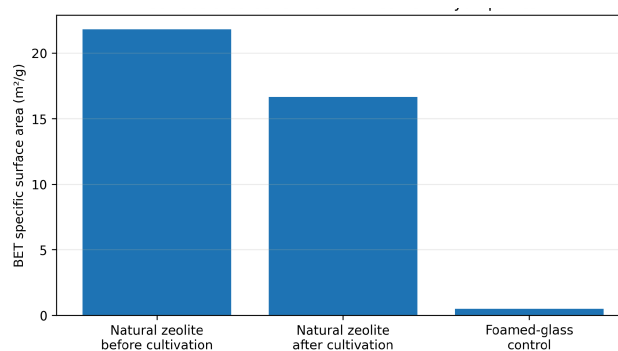


Figure 4. BET surface-area benchmark for natural zeolite used in hydroponics.

Note: Data from Doszhanov et al. (2026), Shankhanai zeolite, Kazakhstan. The figure demonstrates a transferable product concept, not measured Aydag performance.

Catalysis and higher-value product pathways

A direct search of the Aydag's catalogues gives us more proof for diversification approach of products. Mukhtarova and Suleymanova (2026) applied Aydag natural zeolite as heterogenous Catalyst for transesterification of grape-seed oil with methanol. The reported conditions were 65 °C and 120 min, resulting in 92.9 wt.% fatty-acid methyl esters for the process. The study will significantly impact in two areas. First, it is a proof of direct technical use of Aydag material other than adsorption. Second is linking the mineral to agro-industrial waste, as part of the circular economy, which is in line with green-economy objectives.

Catalyst-grade economics are much different from bulk-zeolite economics. But, revenue is not dependent on the tonnage of mined resources, it is dependent on accessibility of active sites within the particles, activation chemistry, catalyst lifetime and regeneration. Although Aydag is natural, the cost of raw materials for catalysts should be decreased but also scale up should take into consideration the conversion per unit catalyst, the separation, the number of recycles, leaching, deactivation and energy required. The margin only matters economically if the higher selling price does not "eat into" that margin, due to the added expense of processing to form the stable catalyst.

Market situations, and techno-economic ranking.

Widespread production of natural-zeolites also reveals a true, if limited, industrial-minerals market. In 2025, natural-zeolite production by worldwide mines was estimated, by the U.S. Geological Survey, to be approximately 1.3 Mt. The top reporting producers were Slovakia, Georgia, the Republic of Korea, China, Russia and Indonesia (USGS, 2026). Selected top producers are displayed in Figure 5. Azerbaijan's position on production is not separately reported in the USGS table; this emphasizes the current lack of transparency at the international level for production's position in Azerbaijan, rather than the lack of the resource itself.

Equal caution needs to be taken with interpretation of the price figure. USGS average U.S. unit values rose from USD 125/t in 2021 to USD 200/t in 2024, with an intervening USD 167/t in 2022 and USD 157/t in 2023. Values are dependent upon percent zeolite, physical and chemical characteristics, particle size, activation and end use as noted by USGS. These figures provide market context with regard to the products of basic zeolite in natural form; they are not applicable to the output of Aydag mine or to the output of catalyst-grade material. The latest average trend in unit values for the U.S. is illustrated in Figure 6. The Aydag cost reported in the literature (120-230 USD/t) is generally on the same order of magnitude as the recent natural-zeolite

unit costs, but is methodologically different because it was reported as a conditional adsorbent cost, not a market COE.

The most robust economic model is thus not a single product (quarry) model, but one of a cascading product portfolio. The higher quality material that is mechanically competent can be channeled to drying for gas; selected or activated grades for water treatment; custom-designed grades for use in catalysts; and less valuable grades into soil, feed-related or construction markets as allowed. This would increase overall recovery, provide for market risk sharing and prevent the need to send all of the ore to costly beneficiation. Furthermore, the portfolio logic affords economic value to the grade-control information since each mineralogical domain can be correlated with the most lucrative specification it is able to achieve. The product pathways and evidence level proposed are provided in Table 4.

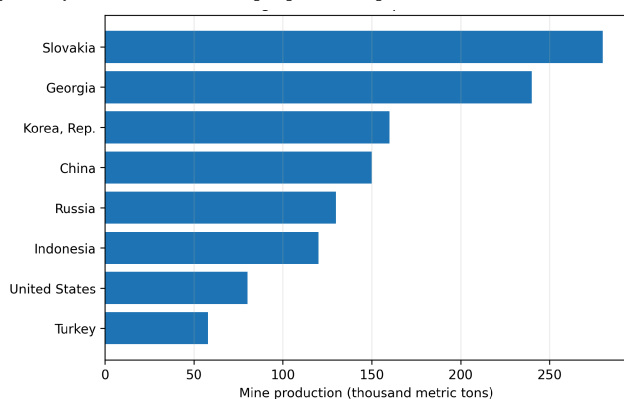


Figure 5. Selected leading natural-zeolite mine producers, 2025 estimate.

Note: U.S. Geological Survey (2026); values shown in thousand metric tons. The chart includes selected leading reported producers, not every producing country.

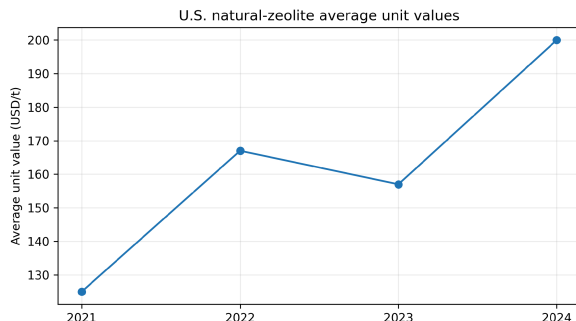


Figure 6. U.S. average unit values for natural zeolite, 2021–2024.

Note: U.S. Geological Survey (2026). Unit values vary by mineral content, physical properties, particle size, activation and end use and should not be interpreted as a current Aydag selling price.

Table 4. Proposed Aydag product pathways and evidence level

Product pathway	Evidence/readiness
Gas drying / purification	Strongest direct Aydag evidence; industrial operation and multi-year performance reported.
Granular water-treatment media	Mineralogically plausible; strong clinoptilolite analogues; modern Aydag breakthrough/regeneration data needed.
Activated heavy-metal adsorbent	Transferable benchmark from other clinoptilolite deposits; Aydag activation optimization required.
Agricultural / hydroponic substrate	Market is established; 2026 hydroponic evidence is from Shankhanai, not Aydag; crop and safety validation required.
Heterogeneous catalyst	Direct Aydag biodiesel evidence exists; reusability and scale-up economics remain to be quantified.

Bulk soil/construction uses	Potential outlet for lower-value fractions; unit margins likely lower and transport distance becomes decisive.
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Information gaps that must be filled prior to making an investment decision.

It should be noted that the current public record is insufficient to make an accurate techno-economic assessment. What is most missing is modern spatially confined resource model related to the quality of the product. An investor should be provided with drill hole coordinates, assays/mineralogy downhole, density, the geometry of overburden and waste and hydrogeology and geotechnical parameters. Minerals variability should be interpreted in terms of its response to processing since the clinoptilolite percentage is not the sole criteria for commercial performance.

Process engineering is the second gap. Crushing and screening tests, along with attrition and abrasion tests, washing, thermal activation, ion exchange, granulation, and regeneration and contaminant-specific adsorption trials should be conducted on representative bulk samples. Mass balance should account for the amount of feed that goes to each saleable product and any lost as fines or reject. This information is crucial in designing energy use, water-demand and designing reagent costs and waste-management.

The third gap is market qualify. For each specific sector, the acceptance criteria are different - in the case of gas-treatment applications, the dew-point and cyclic stability data are requested; for potable-water media, data on leaching and compliance with health-safety specifications; for agriculture, limits of contamination and crop testing; while for customers of catalysts, data on reproducibility, activity and reusability. Therefore, off-take discussions should be held first before the construction of a large processing plant. A phased pilot program can provide sample generation for customers and start to develop data to aid capex and opex estimation. The minimum information which should be available prior to a full techno-economic assessment is listed (Table 5).

Table 5. Minimum information required for a full Aydag techno-economic assessment

Decision gate	Required data
Resource model	Current drilling, density, domain-specific clinoptilolite grade, classification, cut-off and mineable geometry.
Mine plan	Production schedule, stripping/waste ratio, geotechnical design, equipment fleet and haul distances.
Beneficiation	Crushing/screening yields, washing/activation requirements, water and energy balance, product recoveries.
Product quality	CEC, XRD/XRF, BET, particle size, abrasion, leachability, contaminant-specific performance and regeneration.
Commercial model	Verified customer specifications, off-take volumes, ex-works prices, transport/logistics and competing materials.
Economics	Capex, fixed/variable opex, sustaining capital, taxes/royalties, working capital and scenario/sensitivity analysis.
ESG/permitting	Land access, water, dust, waste, biodiversity, rehabilitation, worker safety and community impacts.

CONCLUSIONS

The Aydag deposit is a natural-zeolite deposit that is scientifically established in terms of the presence of clinoptilolite mineral and the high tuff type structure, and has been documented for industrial

function. Available publications show good but site-specific clinoptilolite contents (Gazakh-trough study 2017: ~70-80% in average samples and synthesis CIS resources 2024: ~55-65%). The message to take from this mishnah is not that necessarily one value is wrong, but that resource quality is not homogeneous and that the nature of the analysis is significant.

Most obvious commercially is Aydag specific gas cleaning and drying. Useful moisture & hydrocarbon adsorption over 46 months along with higher crushing resistance compared to synthetic NaA, service life exceeding 3.5 years, and a considerably lower conditional adsorbent cost per source, were reported in the 2021 industrial study. A further evidence of a higher-value pathway is the direct use in catalytic transesterification of grape-seed-oil. Water treatment and agriculture is technically credible but needs to be validated for Aydag and this can be presented as an analogue, the 2026 Plants hydroponic study, but cannot be shown as an Aydag experiment.

The major constraint is quality of data for investment appraisal. Among the recent official/technical sources the estimates of current tonnages range from 20 to 25 Mt and the historical sources report 100 Mt. If we are to leave the development of a modern resource model, beneficiation mass balance, product specifications, capex/opex and verified market prices outside of the equation we will create false precision when calculating the NPV or IRR. The suggested approach is to implement a staged program – characterized resources, mineralogical domains, pilot gas, water, catalyst and agricultural products, customer specifications and finally a complete techno-economic and environmental feasibility study.

AUTHOR CONTRIBUTIONS

Conceptualization, E.A.; methodology, Y.Y.; investigation, E.A.; data curation, E.A.; visualization, Y.Y.; writing—original draft, E.E.A.; writing—review and editing, Y.Y.. The author has read and agreed to the submitted version of the manuscript.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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DATA AVAILABILITY

All numerical data analyzed in this study were obtained from the cited published and official sources. No new field, drilling, laboratory, or mine-production dataset was generated. Values used in the figures and comparative tables are identified by source in the corresponding captions and notes.

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Topographic exposition and agricultural economic potential of land resources in Ordubad district Azerbaijan

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Keywords

*Agricultural economic potential,
agricultural land suitability, ArcGIS,
Ordubad, slope exposition*

ABSTRACT

Solar receipt, near surface temperature, evapotranspiration and soil-moisture conditions are crucially affected by slope exposition (aspect), which can shape the suitability of, and the costs of agricultural activity in mountainous dry areas. This research evaluates spatial distribution of slope exposition in Ordubad District, Azerbaijan and understanding of its implications on agricultural land suitability and agricultural economic potential. An exposition map created from ArcGIS for the district was analysed by six exposition directions such as North, East, Southeast, South, West and Northwest. The class areas and its shares were determined and correlated with the published data on the aspect-sensitive agricultural processes and recent official agricultural indicators for Ordubad. The total area of mapped classification is 1,097.25km². South-facing terrain forms the largest class at 256.58 km² (23.39%), followed by Southeast at 228.18 km² (20.80%), West at 202.16 km² (18.43%), Northwest at 191.17 km² (17.43%), East at 123.61 km² (11.27%) and North at 95.55 km² (8.71%). So, the total contribution of south and south-east exposure is 44.19% of area mapped. The variation indicated by these patterns indicates large spatial variability in heat load, moisture holding capacity and irrigation requirements and hence its potential impact on orchard location, crop selection, water management and farm energy expenditure. In this study, aspect is not an independent suitability criterion, but provides a terrain based screening, in future multi-criteria evaluations slope angle, soils, elevation, irrigation availability and land cover / market factors should be included.

INTRODUCTION

Topography, soils, water availability, climatic resources, accessibility and management are all influencing factors on the suitability of agricultural lands in mountainous and semi-arid regions. Of the topographic factors, slope exposition (more commonly known as aspect) designates the compass direction a slope faces. This orientation affects the amount and time of solar radiation reaching the land surface and as such may impact local temperature, evaporation, snow melt, soil moisture and vegetation. Slopes with opposite orientation in the Northern hemisphere may therefore form different microclimates even if they are geographically near and have a same parent material (Varga & Csiszér, 2020). These microclimatic variations may have implications for agriculture, such as shifts in crop phenology, irrigation needs, frost damage, soil-water storage and field work scheduling.

The value of exposition increases in districts where relief is dissected and divided agricultural areas are to be found in river valleys, foothills and mountain slopes. Ordubad district in the southeast of the Nakhchivan Autonomous Republic of Azerbaijan is a proper case for such analysis. This area is mostly mountainous with a small share of lowland, and development of settlement and agriculture is closely linked to foothill and valley environments. According to the official data of the district, fishing, agriculture, animal husbandry and beekeeping are important activities in rural areas, and that water resources and traditional kahrizi system exist, as well as several rivers suitable for settlement and farming (Ordubad Rayon İcra

Hakimiyəti (Rayon Executive Committee), n.d.). Terrain orientation assumes its importance as a factor, which not only affects the physical-geographic properties but also has economic consequences in land utilization.

The 'agricultural economic potential' in this study is defined as the ability a spatial condition has to sustain an agricultural use that is productive and cost effective, not as a monetary valuation of a land. There are several indirect ways in which exposition can impact the economic performance. An increase in solar loading could increase the irrigation needs, but could also increase the effective growing season or favour heat demanding crops, as depending on the circumstances, it could increase evapotranspiration. Warmer aspects may dry the soil sooner, add some heat stress and limit the performance of some crops and/or delay spring development, while cooler aspects may help to hold moisture in the soil longer and lessen the heat stress. The economic impact thus varies by crop, irrigation method, soil depth, and slope and marketing strategies. This corresponds to the approach of the Food and Agriculture Organization of the United Nations (FAO) to land evaluation, where suitability is not a land quality per se, but depends upon the relationship between land qualities and the requirements of a particular land use (FAO, 1976).

Geographic information systems (GIS) offer a practical way to transform terrain variables into information to support spatial decision-making. Aspect is generated from a digital elevation surface by determining the direction of the downslope for each cell, typically called aspect in degrees clockwise from north (Esri, n.d.). Aspect is often used in conjunction with slope, elevation, soil quality, erosion

risk assessment and land cover and other factors in GIS-based agricultural suitability studies. In the literature, there are also examples of the integration of terrain and soil variables using GIS and Analytic Hierarchy Process (AHP) (Akıncı et al. 2013), and, Kumar et al. (2021) showed the usefulness of GIS-based multi-criteria evaluation for agriculture planning in mountainous area. Also more recent studies on semi-arid Turkey confirm aspect as one of the ecological parameters utilized in land-suitability assessments (Karaelmas et al., 2026).

Also, the application of geospatial evidence complies with the application of geospatial information in green economy and spatial-planning research. Measuring these changes remotely, with indicators derived remotely or in GIS, can illustrate the spatial variations of the environmental phenomena and guide place-specific planning, as is shown in the work of Qadimli and Mammadov (2026). The general principle analyzed in their study is applicable to the treatment of spatial heterogeneity in agricultural research as well, albeit with different impacts: By explicitly considering spatial heterogeneity, environmental and economic decisions are better. Such a source of heterogeneity in agricultural landscapes is exposition.

An economic interpretation of exposition is also associated with the management of energy and water. Agricultural energy needs may feature irrigation pumping, cold storage, processing and greenhouses. Huseynov and Akbarov (2026) highlight the potential of solar and other renewable energy sources to enhance the energy efficiency in farming, particularly through solar-powered irrigation systems. The relevance of this as a terrain in Ordubad with stronger solar exposure would therefore be twofold; this could have an impact on crop-water demand, and it could also show the places where solar-energy assessments in the future could be of particular importance. But slope exposition is not a solar-resource map and direct irradiation, slope and grid-access and technical analyses would be required for any investment decision.

Even though the topography is important for the agriculture of mountains, there is not much research done in the latest years about the directionality of the slopes of the mountain and correlation between them and the agriculture land use and the economy directly in Ordubad. An opportunity to fill this gap at a screening level exists with the existing exposition map. The aim of the present study is thus to (i) quantify the spatial distribution of slope exposition classes in Ordubad District; (ii) interpret the possible impact of slope-direction on agricultural suitability in terms of solar exposure, temperature and moisture processes, and finally (iii) discuss the agricultural economic implications for crop specialization, irrigation, energy use and land-management planning. The analysis focuses exclusively on exposition screening and is not intended to be a comprehensive land-suitability definition.

LITERATURE REVIEW

The methodological history of land use assessment is long and in the context of agriculture planning it has dealt with land suitability. The FAO context of land evaluation is defined as the comparison of land qualities against the needs of specific land-use types, and categorization of the highly suitable, moderately suitable, marginal and unsuitable conditions based on the impact of land constraints on sustained use (FAO, 1976). An important implication of this approach is that none of the physical variables should be understood as depicting an exhaustive representation of suitability. Topography, soil, water, climate, infrastructure and management should be thought of as all one and the same because a land characteristic that is

favorable for one crop or production system could be limiting for another.

Slope is one of the most commonly used variables of topography in GIS based land evaluation, as is aspect. Slope, aspect, elevation, erosion and soil properties were used in the GIS-AHP agricultural suitability analysis by Akıncı et al. (2013) and proved as useful when considering alternative agricultural areas in a spatial evaluation using multi-criteria. Kumar et al. (2021) also fused the topographic, climatic, soil and socioeconomic factors in a mountainous agricultural scenario and concluded that the decision methods using GIS could be useful to focus the limited resources of agriculture to areas where the conditions are more favorable. The reason for the relevance of these studies to Ordubad is these rugged relief may result in creating large environmental differences over short horizontal distances.

The main effect of aspect on agriculture comes in the form of an aspect's control of energy and water balances. Another difference showed opposite slope aspects are compared by Varga and Csiszér (2020) who concluded orientation can result in soil-moisture differences. The physics are firmly understood: slope will affect both when and how much solar radiation falls on a surface, which in turn will impact the temperature of the surface and evaporation and plant-water demand. Solar exposure is often greater on south facing slopes than on those facing north in the Northern Hemisphere, but this varies depending upon the steepness of the slope, the season, latitude, shading and local atmospheric conditions. This translates to an irrigation desirable for early warm weather or heat lit crops also increasing irrigation needs during dry weather.

Aspect is still considered a useful but non-exclusive indicator of agricultural suitability in recent agricultural suitability studies. In a semi-arid agricultural landscape, Karaelmas et al. (2026) combine aspect with slope, elevation, land-use capability, soil depth, soil properties and soil erosion. Their work becomes even more pertinent to the arid micro climate of the interior regions of Azerbaijan, as it shows that besides soil and erosion the aspect-related micro climate should also be considered. Mema et al. (2026) also explores potential for agricultural use in relation to conditions of machinery-management stating that type of land-use and providing physical suitability and operational feasibility should be considered simultaneously to plan any investment and mechanization.

Such integration is especially significant for Ordubad as it is a district that has both mountain slopes and lower valley and foothill farming lands. The official description shows that the climate of the region is arid in summer, with coldness in winter, multi-typed soils, where a significant part of the territory is mountainous (Ordubad Rayon İcra Hakimiyyəti, n.d.). This environment may be a good place to demonstrate those things in exposure. A south facing slope could benefit from the increased spring warmth, but have a higher stress of water during the summer months, and a north or a north west slope could be cooler and retain more water during the summer months. The importance of these contrasts economically will vary with the crop, availability of irrigation water, grade of the land and whether annual crops or orchards are under consideration.

Terrenwise planning can also be applied to Ordubad's agriculture economy as it has an applied rational basis. According to official plant reporting at district level, on 1 July 2025, 193.7 ha of spring crops had been officially reported, of which 89.5 ha was in vegetables, 54.0 ha was in potatoes and 36.4 ha was in cereals and pulses (excluding maize). According to the same source, in terms of horticulture products, 233 t of fruits and berries were harvested by that date, which is 16.2% higher than the corresponding period of 2024

(Ordubad Rayon İcra Hakimiyyəti, 2025). These values are not used here for calculating aspect specific yields as production is not spatially disaggregated in terms of slope direction. Instead, they conclude, that production of cropland and fruit continues to have economic importance, and that the spatial information available on land could be useful in those endeavors.

Terrain and economics are closely connected, and this relationship is reinforced by energy. Huseynov and Akbarov (2026) support that renewable-energy systems can decrease energy pressure in irrigation, greenhouse, storage and agricultural processing activities. Exposition can be important, therefore, both from a biological perspective, because it impacts the heat and moisture regimes, and an operational perspective, because it can be used to prioritize areas for subsequent solar-resource assessment purposes. This link can be aligned with the principles of the green economy where spatial planning aims to increase the productivity of resources and reduce the environmental costs. However, aspect shouldn't be assumed to be the equivalent of solar electricity yield; modelling of direct solar radiation and engineering feasibility are needed.

Hence, there are three propositions to be put forth in this literature which apply to Ordubad. As a first point, aspect is a significant microclimatic factor which can change the soil moisture and heat conditions. Second, it is only partly relevant to agriculture purposes, depending on the type of crop, and has to be combined with other suitability criteria. Third, the economic implications are concerned with productivity (and irrigation demand), operational costs and investment priorities, not just with a one-direction ranking of slopes. The current research agrees with these assumptions and does not consider the exposition map available in ArcGIS as an agricultural zoning map, but rather as a spatial filter.

MATERIALS AND METHODS

Study area

The Ordubad District is located in the south east of the Nakhchvan Autonomous Republic of Azerbaijan, from lowland and foothills in the direction of Zangezur mountain system on the Azerbaijan side of the USSR frontier. According to the description provided by the district administration, the topography of the region is mostly mountain, the government allocates it to a dry-summer, cold-winter climatic zone, a variety of grey, meadow-grey, alluvial-meadow and mountain soils are found there and the agricultural population conducts crop production, livestock breeding and beekeeping. (Ordubad Rayon İcra Hakimiyyəti, n.d.). The district's rivers, traditional water supply systems are of significance since the impact of the slope exposure in a dry landscape is strongly associated with the availability of water supply for irrigation.

The slope exposition map prepared in ArcGIS for Ordubad District is used as the base for the analysis. The map includes a district boundary, regional location inset, satellite basemap and six direction exposition classes—North, East, Southeast, South, West and Northwest. The number of classes and their percentage contributions shown in the map-combined legends are quantitative spatial data for this study. Since the source DEM, the spatial resolution, the vertical datum and the precise angular breakpoints adopted for the reclassification within the six-class classification were not handed over with the final map image, the study does not simulate the original ArcGIS processing nor does it change it. This limitation is so stated explicitly to avoid to represent an unreproducible DEM workflow as a repetition of it.

GIS-based exposition analysis

The compass direction in which the steepest downslope direction

faces is called aspect in arcgis terminology, and is normally expressed in degrees (0–360°, clockwise from north) and not applied to flats (Esri, n.d.). For the given product in Ordubad, these directions (continuously) were taken into account by six author-defined classes of directions. Those classes were left unchanged in the present analysis. No changes were made in the categories provided.

The spatial share was verified for each class (i) through the expression $P_i = (A_i / \Sigma A) \times 100$, where A_i is the area (aspatial) mapped as the class, and ΣA is the total of areas (aspatial) mapped as classes. The six class areas sum to 1,097.25 km². Percentages listed in the map legend sum to 100.03%, which is considered a rounding error, but not a real difference. The mapped area is not a new official estimate of an administrative area, but the area mapped as analytical area supplied with the GIS classification.

Agricultural interpretation was done using a literature-based screening process. Three mechanisms were explored with regard to direction the classes were seen: (1) relative solar exposure and surface warming; (2) likely implications for evapotranspiration and soil-moisture saving; and (3) potential impacts on irrigation requirements and crop selection and costs for farm operations. The point of the framework is to not assign 'numerical ratings of suitability' since an aspect that is good for one crop or season may not be good for another. This method is in keeping with the FAO concept of assessing suitability for a particular land use (FAO, 1976).

For the economic dimension, recent official agriculture information is taken as contextual evidence and not as a spatially-matched dependent variable. Economically relevant crop categories and continuing importance of crop and fruit production were displayed in the 2025 district indicators. Due to the absence of the official data characterising the aspects by virtue of the village parcels or the farms no regression of exposition and output was attempted. Economic potential is then touched upon qualitatively from the points of view of water demand, crop specialization, energy utilization, erosion-control needs and potential incorporation of renewable energies.

The study has four methodological limits. First, aspect is analysed alone, but steepness is of importance for erosion, mechanisation or irrigation design. Second, soils and land cover are referenced from the literature without being spatially analysed and overlaid with the exposition raster. Third, solar radiation can only be inferred in a direction sense and is not directly modelled. Fourth, analysis does not yield crop-specific yield and revenue forecasts. The boundaries imply that the outcome models shall be applied for initial spatial screening and as basis for a second stage of multi-criteria land-suitability analysis, not at the individual parcel level for making investment decisions.

RESULTS AND DISCUSSION

Distribution of slopes with different exposition

In the map with ArcGIS, one can see that there are significant differences in terrain orientation in the Ordubad District. The largest exposure class is south facing exposure, which is found across 256.58 km² or 23.39% of the extent of mapped area. The second largest terrain is southeast with 228.18 km² (20.80%). The South and Southeast classes total 484.76 km² or 44.19% of the total mapped classification. This concentration is significant because the direct sun exposure is typically greater for southerly orientations than for northerly orientations in the Northern Hemisphere, except for during the time of the summer solstice, and depends upon the slope angle as well as any shading of the horizon and elevation.

West-facing terrain accounts for 202.16 km² (18.43%), while

Northwest-facing terrain covers 191.17 km² (17.43%). East-facing slopes represent 123.61 km² (11.27%), and North-facing slopes form the smallest class at 95.55 km² (8.71%). Such distribution represents that mapped terrain of Ordubad does not have a prevailing direction and it has a significant spread on southern, South Eastern and Western directions. This indicates the need for location-specific agricultural management and not district wide assumptions and is an evidence for such heterogeneity.

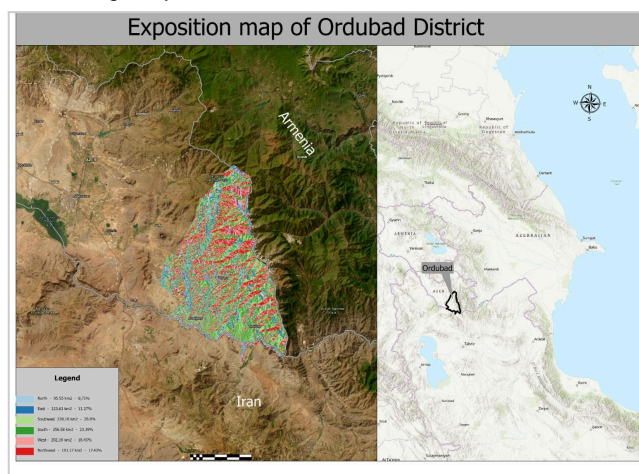


Figure 1. Slope exposition map of Ordubad District Azerbaijan prepared in ArcGIS.

Table 1. Distribution of slope exposition classes in the mapped Ordubad study area

Exposition class	Area (km ²)	Share (%)	Rank by area
North	95.55	8.71	6
East	123.61	11.27	5
Southeast	228.18	20.80	2
South	256.58	23.39	1
West	202.16	18.43	3
Northwest	191.17	17.43	4
Total	1,097.25	100.03*	—

Figure 2 again portrays a proportional pattern. This chart highlights that nearly a quarter of the district mapped is in the South class and another one fifth in the Southeast exposure. Agricultural point of view does not mean that 44.19% territory of Ordubad is suitable for agricultural purposes automatically. A large portion of the district is mountainous and even in favourable exposures, much of the land may be too steep, too rocky, too shallow-soiled, too inaccessible, or too ecologically sensitive for farming purposes. What is instead obtained is an indication as to the location of likely spatially significant aspect related heat and radiation effects in combination with other suitability criteria.

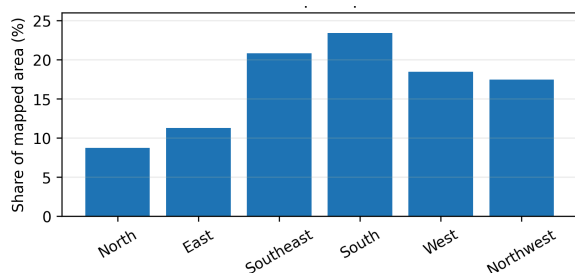


Figure 2. Distribution of slope exposition classes in the mapped Ordubad study area.

Agricultural suitability implications

Special attention needs to be paid to south and Southeast exposures, due to their spatial combination. Within the Northern Hemisphere, these orientations typically have relatively high solar input that can lead to higher spring warming and earlier retreat of snow at the same elevations and under the same thermal environments for crops that benefit from warmth. Carrying over to the orchard realm, in years with a turn-around in the spring temperatures the heat ups can be more of a burden than a help because they lead to earlier bud break and higher incidence of exposure to cold temperatures later in the season. Therefore, the value of agriculture of a warm exposition is climate sensitive and crop specific.

During hot, dry seasons, this same solar benefit may be a water-management concern. Higher surface temperatures can enhance evaporative demand and potentially shorten soil-moisture carry-over. As demonstrated by Varga and Csiszér (2020), aspect (or slope) may be related to quantifiable soil-moisture differences even in the same site class. On the long benches of Ordubad, with its significant problems of summer dryness and irrigation, this mechanism suggests that more attention might be needed for irrigation scheduling, mulching, soil-cover management or using drought-resistant crops on South and Southeast slope exposures than on cooler slopes. Water and energy, therefore, offset the economic benefits of the early warming.

The afternoon loading of parallel rays could be great for a west-facing slope of 18.43% of the mapped area, especially if it is hot during the afternoon. During the summer months this combination could contribute to increased late day heat stress and evapotranspiration. This land is not inherently unsuitable, but irrigation efficiency can be important for high-value horticulture areas without other ways to decrease excess thermal environment, and other soil-moisture diffusion monitoring and, where agronomically suitable, vegetation-management or orchard-management options can also provide this benefit. East facing slopes expose crops to more direct radiation during the morning when temperatures tend to be cooler, and this exposure may provide a more moderate heat regime throughout the day for some crops.

Together, the North and Northwest exposures cover 26.14% of the area mapped. These exposures tend to have less direct solar exposure than South exposures in the Northern hemisphere, and can hold more moisture if all conditions are the same. In some crops, cooler air may extend the effective thermal period of the development or retard the ripening; in other crops, cooler conditions may be beneficial where summer temperatures and/or moisture shortages are critical. Economic interpretation thus varies according to production goals. Water-saving exposures might help to minimize the need for irrigation, while those crops that need more heat accumulation to grow may benefit from warmer exposures if water supplies are sufficient.

The aspect-related compromise explained the reason for considering aspect as a differentiability in a bigger framework of land-suitability. Karalmas et al. (2026) and Akıncı et al. (2013) apply the aspect criterion along with a number of ecological and soil criteria. In the future, an Ordubad assessment should also be able to follow a logic of exposed Ordubad, then slope gradient and elevation, then soil depth, then erosion susceptibility, then land coverage and then access to roads and restrictions of protected areas. These layers will only be consolidated then should land be categorized as highly suitable, moderately suitable, marginal or unsuitable for a particular crop or production system.

The economic potential and the context in which agriculture is currently being practiced.

Current production indicators suggest the agricultural importance of terrain screening. The Ordubad District Executive Authority reported that 193.7 ha of plantings were experiencing the spring crop stage in July 25th. The area dedicated to vegetables, potatoes, and cereals and pulses – excluding maize – was 89.5 ha, 54.0 ha and 36.4 ha, respectively. By the same date, 233 t fruit and berries were harvested, which was 16.2% more than in the corresponding period of the previous year (Ordubad Rayon İcra Hakimiyyəti, 2025). These numbers are representative only of district-level activity, and therefore cannot be directly related to classes at exposition, but they do indicate that horticulture and the production of field crops are important parts of the local economy.

Exposition may affect the product quality and management cost in fruit production. Warmer slopes may provide earlier maturing crop and/or possible greater selection of heat demanding species/cultivars and cooler slopes could have known value for production of heat moderated crops or crops benefiting from improved moisture retention. Orchards, simultaneously, are long-term investments and can be committed for many years to higher costs due to an unfavourable combination of aspect, frost risk, shallow soil or water shortage. The utilization of topographic screening before orchard planting should therefore be an effective tool in minimizing the investment of misallocated capital in addition to soil testing and irrigation assessments.

Water production is a key economic pathway. If a warmer exposition increases evapotranspiration, the farm will have to pump more water leading to higher costs, increased need for labour to manage the process and higher propensity to various levels of water shutoffs. A cooler or more moisture conserving exposition on the other hand, might lead to fewer irrigations but a different production calendar. These mechanisms imply that aspect will not only impact on biophysical suitability but also on variable cost and risk. A future framework of farm economics could do so by quantifying the water use, electricity use, pumping head, and crop yield and output prices by parcel.

Additionally, energy innovation is an opportunity. By investigating the potential applications of renewable energy, Huseynov and Akbarov (2026) find that solar-powered irrigation, greenhouse energy supply, cold storage, and other applications contribute to reducing the energy use in agriculture. With a large percentage (44.19%) of the mapped Ordubad classification exposed to the South and Southeast, there could be significant areas of landscape that warrant further exploration for solar-energy integration opportunities. In the current state of the model aspect map, however, it is not possible to extract the PVs yield. The necessary information for a proper feasibility study should be obtained as solar irradiance, slope gradient, shading, land-use conflict, location of the grid or pump, thickness of equipment cost and water-demand data. This means the conclusion isn't one of direct investment fare, but one of research prioritization.

The broad geographical planning context also proves to be beneficial for the economic interpretation. Spatial environmental indicators can demonstrate spatial patterns that are hidden from average statistics, and can be used for targeted planning, as demonstrated by Qadimli and Mammadov (2026). The same holds true for the Ordubad case: Potentially, agricultural support policies, orchard modernization, irrigation modernization and renewable-energy projects should be targeted with parcel- or village-level spatial information. A district-wide average crop does not display if specific terrain

orientations systematically encounter higher water costs, or different thermal conditions.

Table 2. Selected Ordubad agricultural indicators reported for 1 July 2025

Indicator	Reported value
Spring crops planted	193.7 ha
Vegetables planted	89.5 ha
Potatoes planted	54.0 ha
Cereals and pulses (excluding maize)	36.4 ha
Fruit and berries harvested	233 t
Change in fruit and berry output	+16.2% y/y

Aspect-related planning matrix

Table 3 summarizes the direction-specific interpretation adopted in this paper. The table is intentionally qualitative. It does not label any direction as universally 'best' because the economic effect depends on the crop, season, slope steepness, irrigation access and soil properties. Instead, it identifies the principal mechanisms that should be evaluated during more detailed agricultural planning.

Table 3. Distribution of slope exposition classes by area and percentage in Ordubad District

Aspect	Likely microclimatic tendency	Indicative agricultural-economic implication
North	Lower direct solar load; cooler and often more moisture-conserving	Potentially lower summer water stress; slower warming may constrain heat-demanding crops
East	Morning solar exposure; moderated afternoon heat	Potentially balanced conditions for orchards/vegetables; site-specific frost and water analysis needed
Southeast	Strong morning-to-midday exposure	Good thermal potential with irrigation; attractive for horticultural screening
South	Highest relative solar load in many seasons	Longer/warmer conditions but potentially higher evapotranspiration and irrigation-energy cost
West	Strong afternoon heat load	Potential heat and water stress; may require efficient irrigation and heat management
Northwest	Cooler late-day regime; lower direct solar than southerly slopes	Potential moisture conservation; suitability depends on crop heat requirements

Crop-specific planning priorities

When the main agricultural activities of Ordubad are examined separately, the exposition pattern is principled to be translated into more practical questions regarding planning. The main problem, in orchards, is the combination of duration of the crop investment and site microclimate. For exposures that vary in heat accumulation, temperature differentials in spring warming and water requirements may affect the productive life of an orchard with tree crops or the orchard maintenance costs. Detailed field evaluation might be warranted for southeast and east exposures where the morning sun would be welcome but afternoon heat would be excessive, and south exposures might be more suitable for cultivars that do better in warm exposure where irrigation was reliable and the soil was deep.

The economic situation of vegetable growers differs in several respects because of the more short period cropping and the ability to make adjustments more quickly. Early season vegetative production may benefit from the accelerated soil temperature rise and earlier harvest

dates on warmer exposures, which may enhance market-timing. All the same land can now get more expensive in the middle of the summer when evapotranspiration and the frequency of irrigation grows. In view of this, it would be preferable to present results in terms of a crop calendar rather than one annual suitability score. Seasonal suitability maps may include a separation of production benefits in the spring from water stress risks in the summer and may be useful for more efficient planting window decisions.

Crop specific interpretation is also necessary, for example potato production. The potato needs sufficient soil moisture; may be chilling injury sensitive during tuberizing. Therefore, cooler East, North, or Northwest exposures could be economically relevant and warmer South, Southeast exposures could allow for earlier production if they are lower in elevation and irrigation and soil conditions are good. These statements are hoped to be true Ordubad yield responses but have not been measured. Field tests should be conducted to compare the phenology, irrigation volume requirements, production and product quality of similar field areas that are situated in different expositions.

Exposition for cereals, pulses and fodder systems can take on the form of moisture conservation, risk of erosion and mechanisation conditions. In general, annual crops grown in fields have less value per hectare than intensive orchards or vegetables so that the proportionate effect of irrigation and terracing or erosion-control costs may be greater on the profitability of such crops. Thus, aspect and slope angle play a significant role. Even if the land can be cropped with plants, there may be limitations on the land's potential value for economically viable use of annual crops because of steepness or erosion problems.

Following the same reasoning, the suitability layers that come out of an extension of the present work should be different depending on the crop in question, instead of a single suitability map for farms in general. Commonalities of exposition, soil, slope, water and access could be incorporated into the models for orchard, vegetable and potato growing and field crops with some changes as to weights and thresholds. This differentiation would be in line with the FAO concept of land suitability, which refers to a particular land use (FAO, 1976), and would help enhancing the base for agricultural investment, extension services and planning with resource efficiency.

For sustainable land management:

Based on the results it is recommended that Exposition as a management variable should be considered and used in sustainable planning of agriculture in Ordubad rather than as a cartographic descriptor. Areas that are warmer (South and Southeast) might prioritize efficient drip irrigation; soil-cover conservation; organic-matter improvement and crop selection to more thermal and evaporative demand. For cooler directions, management will focus on maximizing the heat requirement of the crop within the growing season that is available locally and taking advantage of moisture opportunities without inviting disease or frost exposure. These measures can help to minimize crop/site mismatches.

When this information is combined with slope gradient, it can also be used to aid in erosion and land-conservation planning. While aspect alone is not controlling, solar exposure influences the vegetation cover and soil dryness, as well as the velocity of the surface runoff and mechanisation constraints are influenced by the steepness of slope. A combined slope-aspect model should therefore be the next step of the analysis. However, steep and high exposure areas may be best suited for permanent vegetation establishment, orchard terracing if appropriate, conservation grazing and/or other practices as alternatives to annual tillage.

The Entire GIS layer has a green economy impact based on optimizing resources. Improved site selection can lower a need for unnecessary irrigation and fertilizer, failed orchard establishment and energy use. It can also aid in better targeting of solar powered pumping or other renewable energy interventions as mentioned by Huseynov and Akbarov (2026). Spatial targeting is especially relevant when capacity to invest in agriculture is scarce as investments in irrigation, farm roads or energy infrastructure have very long lives and should ideally be invested where several suitability conditions overlap.

This proposed framework is also applicable to extend in a multi-criteria decision model. In the future it could be beneficial to use another GIS-AHP analysis that would allocate weights to slope, aspect, elevation, soil depth, soil texture, irrigation distance, road access, land cover and erosion risk separately for orchards, vegetables, potatoes or fodder systems. This would not only take the analysis away from a general terrain screening, but also to land-use based suitability classes. Akinci et al., (2013), Karaelmas et al., (2026) and Mema et al., (2026) offer compelling instances of methodology implemented at this subsequent stage.

The drawbacks and further studies are introduced.

The only problem is the lack of an actual original DEM and ArcGIS project in order to have the map exported. Before final publication, the azimuth ranges for the six classes, the area computation coordinate reference system, the cell size and the DEM source should be documented in a project archive. This information will allow the independent reproduction and sensitivity analysis. The analytical area on the map (1,097.25 km²) should also be verified with the official administrative area in the GIS project to see if there is any buffer, neighbouring terrain or projection related area difference.

A second constraint is the lack of specific crop information at spatial level. The map works at a terrain-cell level and current official production data is available by district. Consequently, the work fails to test the hypothesis that south, south-east or other directions have a real effect upon increased yield or decreased costs in Ordubad citrus orchards. In the future it is necessary to geocode orchards and crop parcels and perform yield measurement and irrigation volume measurement and to bring back the following field data, namely, soil data, cultivar and farm-cost data. This would enable statistical testing of exposition effects with elevated effects controlled for; and slope effects and management effects.

Third, direct solar radiation, temperature and evapotranspiration were not modelled. It is important to note that Aspect is not the same as these variables, but is a controlling factor of them. In the future, a DEM-based model of solar radiation along with the seasonal temperature data would be used with the water-balance indicators and remote-sensing vegetation indices. To measure in the field the physical mechanisms proposed in this paper and to tie in terrain with water and energy needs would enhance the economic analysis with this type of integration.

Lastly, protected areas and land not under agriculture such as settlements, infrastructure, unstable slopes should be excluded from land-suitability analysis, or separately classified. The terrain classification included in the present map of the mapped district is not to be interpreted as an invitation to extend the scope of agricultural activity in the environment sensitive areas. The economic potential can be sustainable only if efficient use is made of already suitable or responsibly developable land and not costly and valuable natural ecosystems.

CONCLUSIONS

The present study is aimed at an aspect based screening of agriculture land suitability and agricultural economic potential in Ordubad district in Azerbaijan. According to the ArcGIS exposition map, the terrain mapped shows a greater exposure of South 23.39% and Southeast 20.80% exposures that cover 44.19% of the classified area. The difference between West and Northwest exposure is another 35,86% and the rest smaller amounts with East and North. The distribution shows that there is appreciable microclimatic variation within the district, and agrees strongly with the concept that in planning for agriculture the direction of the terrain should be taken into consideration instead of assuming the district to be an homogeneous production area.

This pattern in agriculture is subject to conditions. Favourable thermal conditions and greater solar input are possible with south and south-east exposures, but in a dry mountainous setting they can also lead to greater evapotranspiration and irrigation requirements. North and Northwest exposures will help maintain moisture and minimize heat stress, and will likely result in decreased thermal accumulation for certain crops. The different characteristics of the east and west exposures (solar exposure during different parts of the day) may have implications for issues of heat stress and water management. As a result, without crop requirements and other land characteristics into account, no exposition class may be classed, in general, as universally suitable or unsuitable.

The economic implications are basically through the management cost, production risk and investment targeting. Present district data show that the production of vegetables, potatoes and cereals and fruits are still important industries. Using aspect-aware planning can assist in placement of crops or orchard stock that will be more likely to take advantage of local thermal and moisture conditions and decrease irrigation demand or risk of inappropriate long-term plantings. It is further noted that the majority of the territory is located in the south and, therefore, future research is also recommended in the field of solar-powered irrigation and other renewable-energy applications, as specified by Huseynov and Akbarov (2026). This investment however depends upon the availability of solar resource and not only the aspect but in addition engineering analysis.

The central policy recommendation is thus a broader connection between the existing exposition layer and agricultural decision-support system based on GIS. Factors such as slope gradient, elevation, soil depth and texture, erosion susceptibility, irrigation distance, road access, land cover and the protected area status and crop specific requirements should all be considered priority factors. Then the farm information should be added at parcel level and quantifying the yield, water use, energy use and profitability should be added. This would allow to switch from qualitative screening to suitability and economic optimization per crop.

This study does not present a final map that zones agricultural activity, but is a clear initial step toward integrating the terrain orientation with agricultural and economic decision making. The analysis is intended to provide a relatively simple GIS product applicable to a more accurate, sustainable and green-economy oriented agricultural planning in Ordubad, by indicating the agroecological conditions where each can prosper, and by illustrating the processes by which such conditions can influence production costs and resource utilization.

AUTHOR CONTRIBUTIONS

Conceptualization, U.Y.; methodology, U.Y.; GIS analysis and cartographic preparation, U.Y.; data curation, U.Y.; formal analysis, U.Y.; visualization, U.Y.; writing-original draft, U.Y.; writing-review and editing, U.Y. The author has read and approved the final version of the manuscript.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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DATA AVAILABILITY

The spatial results analysed in this study are contained in the ArcGIS-derived exposition map supplied by the author. The map-level class areas and percentages used in the analysis are reported in Figure 1 and Table 1. The original DEM and ArcGIS project files should be archived with the author for reproducibility before final publication. Official agricultural statistics cited in the study are publicly available from the Ordubad District Executive Authority and the State Statistical Committee of the Republic of Azerbaijan.

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Agribusiness marketing in transition: Current trends and strategic implementation in Azerbaijan

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Keywords

Agricultural marketing, digital technologies, agro-parks, branding, value chains

ABSTRACT

This paper investigates the shift from traditional marketing channels to digital, brand and coordinated market systems in the agribusiness marketing of Azerbaijan. It is a descriptive-analytical design, which includes a thematic review of relevant literature and policy documents, followed by secondary analysis of the official agricultural indicators and a strategic assessment of logistics, certification, digitalization, agro-parks and cooperative frameworks. The indicators compiled indicate that total agricultural output was about AZN 14.19 billion, wherein the share of crop output was 47.6 per cent, and the share of the livestock sector amounted to 52.4 per cent and agricultural exports were found to be about USD 936 million, among which the share of fruits and vegetables was significant. It was identified that digital platforms, direct-to-consumer linkages, regional branding, certification, agropark integration and co-logistics can bolster market linkages and value appropriation. Fragmented structures in agricultural production, as well as differences in digital skills, marketing capacity and storage and transport capacity also continue to hinder competitiveness. Proposals for regional value-chain orientation based on geographical identity, digital traceability and a logistics-sharing cooperation. The results clearly indicate that market support through better coordination of market institutions, infrastructure, quality assurance, finance, and digital tools play a pivotal role in boosting the competitiveness of Azerbaijan's agribusiness sector in the domestic and export markets.

INTRODUCTION

Despite the relative significance of agriculture as a part of non-oil sector of the Azerbaijani economy, the competitiveness of agribusiness is now dependent not only on increase in volumes of production but also on a range of additional factors. The effectiveness of the transformation of agricultural output into income depends on market access, product differentiation, logistics, quality assurance and the ability to adjust when there are changes in the consumers' demand. The production environment has been bolstered by government support measures, export promotion, and the development of agro-parks, while new channels of communication among producers and buyers have emerged with the digitalization of production, which makes it easier for producers to reach markets (Ministry of Agriculture of the Republic of Azerbaijan, 2024; World Bank, 2023). Therefore, in the modern times agricultural marketing has not only happened when products are physically transported from the farm to the consumer but before that as well. It entails market research, e-commerce, branding, certification, digital communication, value-chain coordination. Seasonality, perishability, and the variability in quality make these functions especially significant for agricultural commodities, as timely information on the market is important and efficient distribution is essential (Food and Agriculture Organization of the United Nations [FAO], 2023; International Food Policy Research Institute [IFPRI], 2023). Producers may have limited control over their product if these functions are insufficient and this

can lead to increased post harvest losses and reduced final market share.

The level of introducing modern marketing tools is not uniform in Azerbaijan. The use of digital platforms and social media has become apparent, however, small producers continue to have difficulties in marketing knowledge, storage, transport, certification, and access to coordinated sales system. While some previous research and policy reports focus on one or more specific aspects of development (e.g., digital agriculture, food security, or cooperatives), less is written about the interaction between different aspects when it comes to export development in an agribusiness marketing system (Huseynov & Guliyeva, 2022; Mammadova & Mammadov, 2025). This calls for a formal and systematic evaluation that links market trends to institutional and infrastructural situations.

In this regard, the current trends of agribusiness marketing in Azerbaijan and the necessary strategic conditions to provide effective implementation will be assessed. The analysis will answer the following questions: (1) What are the structural factors that affect the marketing opportunities and constraints in the agricultural sector, (2) What are the marketing effects and the possibilities of digital marketing together with branding, certification, agro-parks and the cooperative principle, and (3) How can these be put together in a cohesive framework of regional value-chains. Secondary information is used and thematically synthesized to yield strategic implications but not causal estimates.

LITERATURE REVIEW

Agricultural marketing/ value chain coordination

Agricultural marketing involves functions like aggregation, transportation, storage, processing, pricing, promotion and selling that link production to final demand. It plays a particularly important role in the case of perishable products and where supply is seasonally and/or climatically influenced. In such situations, market information and coordinated logistics can help to mitigate uncertainty and ensure production decisions align with market demand (FAO; 2023; World Bank; 2023). Efficient marketing systems thus play a part not only in sales but also in the organization of the market chain in general.

Traditional market systems (local markets and middlemen) can function as a direct path for producers to market, but can also give consumers the upper hand and exclude producers from information. Some of these constraints can be overcome by adopting ICTs, producer-to-consumer marketing and cooperative marketing, which expand the knowledge base and provides alternative marketing avenues (Organisation for Economic Co-operation and Development [OECD], 2021). But whether these alternatives are effective requires supporting infrastructure such as storage, transport and fulfillment.

Digitalization, branding and quality assurance.

Social media, online marketplaces and even communication through the use of data make it a low transaction cost for connecting the producer with the consumer which has made digital marketing an important part of the contemporary agribusiness. The information on origin, quality and availability of products is also communicated more directly via digital platforms. At the same time, branding can be used to distinguish agricultural products, which are often subject to competition predominantly based on price, and certification can mitigate information gaps by certifying adherence to established quality and/or safety standards (European Commission, 2022; OECD, 2021).

The relationship of branding and quality assurance is especially relevant with the export-oriented agribusiness. Although regional branding can boost product awareness, it is equally vital to ensure equal standards, traceability and delivery. Therefore, branding should not only be regarded as a purely promotional exercise, but backed up by production discipline, through certification and logistics. This integrated perspective aligns with the research that highlights the significance of regional value chains and market institutions in emerging markets (European Bank for Reconstruction and Development [EBRD], 2023).

Institutions, clubbing, cooperative and financing

Marketing can be reinforced through the creation of agro-parks, clusters (groups) of agricultural operations and cooperatives, so that the activities that are more difficult to coordinate at the individual small farm level would be brought together. The integration of production, processing, packaging, storage and selling can enhance the standardization of interlinkages and minimize transaction costs, and synergized infrastructure can provide for bigger and more stable volumes of the markets (FAO, 2023; Ministry of Agriculture of the Republic of Azerbaijan, 2024). The key to facilitating access to logistics and market information is also through cooperative arrangements, which, however, requires good governance, trust and unambiguous economic incentives (United Nations Development Programme [UNDP]; 2022).

Financing is also pertinent to the transition towards technology-driven and resource-saving agribusiness. Using green finance instruments to advance solar energy development in Azerbaijan, Sadiqov et al. (2026) show the importance and function

of targeted financial mechanisms in providing capital-intensive investment opportunities for low-carbon energy. In fact, some financial concepts can be generalised to renewed-energy-based irrigation, cooling in the agribusiness field, and processing and logistics, but are not tested here.

Collectively, the literature implies that a relationship between market information, digital market, infrastructure, quality assurance, institutional coordination and finance is crucial for effective agribusiness marketing. The core analytical gap filled in this paper will not be the usefulness of these instruments per se, but rather how they may be integrated into an implementation framework that is appropriate for the agricultural structure of Azerbaijan.

MATERIALS AND METHODS

Research design and analytical framework. Research design and analytical framework.

The type of research used in the study is descriptive-analytical using secondary evidence. It involves a qualitative, thematic synthesis analysis and a descriptive analysis of agricultural production and agricultural export indicators. No primary survey, experiment nor causal econometric model is applied. The goal is to find structural marketing patterns and to make strategic interpretations based on the available evidence, not to make causal estimates.

The data sources and the analytical procedure are reported.

The empirical base is comprised of secondary information provided by the State Statistical Committee of the Republic of Azerbaijan, INSTC of Azerbaijan, the Ministry of Agriculture of the Republic of Azerbaijan as well as international organizations such as FAO, OECD, EBRD, the World Bank, UNDP, the European Commission and IFPRI. The literature and policy materials were analysed under five main themes: Digital marketing, branding and certification, logistics, institutional coordination, and market access. The structure of agricultural output and exports was described by means of quantitative indicators.

The analytical procedure has been done in three phases. Initially literature was synthesized and main functions and constraints of modern agriculture marketing was emerged. Secondly, the available indicators of the different sectors were classified as to the relative importance of crop production, livestock production and export-oriented production. Third, the evidence was considered with a strategic perspective and an analysis was carried out regarding the potential flexibility of the agrarian context in efficiently overcoming the identified constraints through the use of digital tools, regional branding, local agro-parks, cooperation, and shared logistics. Since some of the figures have been given as an approximation, and the sources are also diverse as secondary indicators, so the results have to be taken as evidence of the prevailing situation and not a continuous statistical series.

RESULTS AND DISCUSSION

Structural profile and marketing implications

This study's sectoral indicators reveal a significant level of agricultural output with reasonably even split between crop and livestock farming. At overall agriculture output is approximately AZN 14.19 billion, out of which agriculture (crop) production is roughly 47.6% and livestock production 52.4%. Exports, mainly in agricultural products, are valued at USD 936 million, among which fruits and vegetables have a significant role. Such patterns suggest that marketing success is hinged on the coordination between domestic supply-chain and on the capacity to fulfill the demands of export market.

Table 1. Key indicators of agricultural production and marketing relevance in Azerbaijan

Indicator	Approximate value and marketing interpretation
Total agricultural output	AZN 14.19 billion. Indicates a sizeable production base and continued need for coordinated market infrastructure.
Crop production	About AZN 6.75 billion (47.6%). Perishable and seasonal products increase the importance of storage, cold-chain capacity, and timely market access.
Livestock production	About AZN 7.44 billion (52.4%). Market performance depends on feed supply chains, processing, quality control, and domestic distribution.
Agricultural exports	About USD 936 million. Fruits and vegetables account for a substantial share, reinforcing the importance of export branding, certification, and logistics.

Note. Values are approximate indicators compiled from the State Statistical Committee of the Republic of Azerbaijan (2024) as presented in the study materials.

This is particularly significant in relation to marketing since value chains in fruits and vegetables are sensitive to the value and packaging of produce and time to market. Poor storage or transport can lead to a rapid decline in quality, and reduced prices realized. Processing and cold chain management and quality standardization are also demanded, due to the livestock production scale. In this context, production growth by itself is not enough to make production more competitive; marketing infrastructure plays a crucial role in retaining how much value is retained and transferred along the value chain (EBRD, 2023).

State support has been growing, contributing to the institutional basis for the modernization of agriculture through providing subsidies, preferential financing, infrastructure and the development of agro-parks (Ministry of Agriculture of the Republic of Azerbaijan, 2024). The strategic significance of agricultural marketing has also grown with the export promotion initiatives and overall focus of non-oil diversification. These measures provide potential opportunities, however, if producers are able to ensure regular product quality, supply and market linkages from the support measures, they will impact the market.

Direct to consumer channels and digital marketing

Certain communication barriers that exist between producers and consumers have decreased through use of digital platforms/social media. It allows farmers and agribusiness to advertise for products, get orders, to provide origin details and respond faster to market demands, through online sources. Direct sales may also lessen reliance on middlemen and potentially boost producers' share of the final value, (OECD, 2021). The benefits are especially applicable to niche, premium and area differentiated products.

Digital marketing isn't a replacement for physical distribution, however. Online orders also need something that is securely packaged, stored, conveyed, paid and delivered. The advantages of digital are thus constricted when the logistics are not strong, and/or when producers do not have the knowledge and skills needed to create the digital content, handle the customer interactions and deliveries. This is what makes the digital transformation a process that should be planned as a marketing-logistics process, and not only social media or e-commerce application acquisition process (Huseynov & Guliyeva, 2022).

Branding, certification and competitiveness of exports.

Branding could be a way to differentiate Azerbaijani agricultural products from those based on their physical characteristics. Geo-positioning, quality, and authenticity can be used as positioning products associated with a particular region or production tradition. Hazelnuts, pomegranates, grapes and apples are all listed in the manuscript as products with regional branding potential. Product associating with its place of origin can be helpful for differentiation both in local and global markets (Karimli, 2024).

But brand value cannot be sustained without quality support. International standards and certification will help build consumer and buyer confidence, especially in export markets where food-safety and documentation requirements are formalized (European Commission, 2022). Digital traceability can serve as an additional tool for certification and provide more information on origin, handling and movement of products. Strategically, there is two models that are therefore effective: the combination of the regional identity with a Quality Assurance model and the presence of traceability, and, at the same time, dependable logistics.

Agro-parks, clusters and cooperative marketing

An institutional mechanism for integrating production, processing, packaging, storage, and sales is offered by agro-parks and clusters. This sort of integration could benefit standardization, and break down volumes when bigger buyers require it. Furthermore, it can help establish a unified segment of the value chain (FAO, 2023; Ministry of Agriculture of the Republic of Azerbaijan, 2024) by adopting the methods and technology of quality-control systems. These functions are critical for export-oriented production activities since the international buyers would demand regular volume, quality and delivery schedule.

Smaller farms can achieve similar benefits from cooperative marketing, but marketing cooperatives need to be formed around practical shared resources. However, cooperatives are not restricted to only collective production or negotiation, but could also share cold storage facilities, transportation, packaging, certification and market information. This will help to minimize duplication of fixed costs and connect buyers (Aliyev, 2023; UNDP, 2022). This is the organizational sustainability: A shared system needs an open governance and for the membership to have incentives to continue participating to make it economically rational to do so.

Major constraints and development opportunities

Four constraints are at the core, even though more and more support measures and digital possibilities are created. First, it is difficult for farmers to standardize and market in large volumes due to farm fragmentation. Secondly, lack of warehousing, cold storage and transport facilities can diminish the quality and position of the Perishables market. Third, producers don't all have the same ability when it comes to marketing and digital skills. Fourth, concerted action among producers, processors, logistics suppliers and public institutions is needed with regards to certification, traceability and brand development. These constraints compound each other and can only be addressed effectively by addressing more than one constraint in isolation.

The development perspective is good as there is clear scope for specific development based on the same constraints. Value chains can be strengthened through investment in shared logistics, training of producers, digital platforms, regional branding and quality systems. Agro-parks and clusters can offer organisational structures that allow such a coordination to happen, and export-oriented brand can offer incentives for this. The central policy implication is to create a marketing modernization as a system, in which the upgradings and

developments of infrastructure, skills, standards, digital tools and financing support each other.

Strategic implications and proposed contribution In what ways could the content help people make decisions related to strategic business issues?

Based on the study, the researchers have suggested three strategic modifications to the traditional agribusiness marketing methods. First, the aim of branding should be related to its origin and product identity and not used as a generic promotion. Second, certification should be backed up by digital traceability and logistics, so quality statements can be backed up along the way. Third is the need to give greater priority to cooperative marketing for shared logistics and cold chain infrastructure as it has direct impact on the quality of post harvest and market access.

The regional value-chain integration model is represented by these propositions and can be applied in the regions where agricultural market systems are in the organizing process such as Karabakh and East Zangezur. Within this kind of environment the regional identities symbols can be linked to digital traceability and logistics coordination, and gradually change the way of dealing with commodity sales into a value-added market positioning. The framework is conceptual and should be viewed as a strategic proposition, based on the synthesis, and not one that has been tested for causes.

Table 2. Strategic interpretation and proposed contribution
Conventional view

Conventional view	Strategic proposition of this study
Branding increases product value.	Link branding to regional origin and product identity to strengthen differentiation.
Certification builds consumer confidence.	Reinforce certification with digital traceability and reliable logistics across the value chain.
Cooperatives strengthen bargaining power.	Use logistics-sharing, cold storage, packaging, and market information as practical foundations for collective market power.

The conceptual contribution in the table should not be interpreted to mean that the proposed relationships have been confirmed by experiment. Further firm-level and farm-level studies could evaluate the impact of these integrated arrangements on hard metrics for gains in price, market access, post harvest losses or export performance.

CONCLUSIONS

As it was revealed in the results of the study, the production structure, digitalization, logistics, branding, certification, institutional coordination and finance are the indicators of the transition of agribusiness marketing in Azerbaijan. Available evidence shows that there is a significant agricultural base and export potential, though the ability to add value to the product of the farms is limited by the poor marketing competences of farmers, fragmented farm sizes, as well as inadequate storage and transport facilities. Digital platforms and direct sales do provide opportunities to access the market but need robust physical distribution and producers' capacities.

The analysis also indicates that "regional branding", "quality assurance", "digital traceability", "agro-parks" and "shared logistics" should be considered as complementary strategies and not different interventions. A value chain model based on a product identity, traceability and cooperative logistics is a workable approach for boosting competitiveness. Priorities for policies and investments should accordingly focus on the development of cold-chain infrastructure, marketing and digital training, certification capacity based on cold-chain infrastructure development, coordinated export branding, and access to the right financing for cold-chain infrastructure and technology.

The study has drawbacks in using sources secondary to the primary sources, sectoral indicators approximate, and the non-existence of primary data for even the farms and the firms. Does not measure causal effects or the effectiveness of particular marketing actions. Future research ought to validate the proposed framework by means of producer-surveys, data from buyers, value-chain cost analysis and longitudinal indicators, so as to calculate the economic impact of digital marketing, regional branding, traceability as well as logistics-shares.

AUTHOR CONTRIBUTIONS

Conceptualization, methodology, investigation, data curation, formal analysis, and writing—original draft, L.Z.H. and M.J.H.; writing—review and editing, L.Z.H. and M.J.H. Both authors have read and approved the final version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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DATA AVAILABILITY

The study is based on secondary data and institutional reports cited in the manuscript. No original primary dataset was generated for this study.

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Passive CO₂ capture and mineralization on existing mineral building surfaces: A falsifiable framework for Low-Operational-Energy carbon removal

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Keywords

*Direct air capture; mineral carbonation;
building envelope; moisture swing;
passive carbon removal*

ABSTRACT

Active direct air capture requires dedicated air contact, sorbent regeneration, and associated operational energy. This study theoretically examines a complementary concept in which existing mineral building surfaces act as distributed passive air contactors. The proposed Passive Carbon Skin architecture spatially separates reversible atmospheric CO₂ capture, climate-mediated carbon transfer, and mineral fixation within a Ca- or Mg-rich reservoir. Rather than claiming a validated material, the study defines a falsifiable system framework, closed carbon-balance boundary, theoretical capacity limits, climate-dependent operability variables, and an experimental validation pathway. For an illustrative Mg(OH)₂-based baseline containing 180 g Mg(OH)₂ m⁻², the stoichiometric storage ceiling is approximately 136 g CO₂ m⁻²; achievable retention remains unknown and depends on reaction kinetics, thermohygrometric cycling, transfer efficiency, passivation, weathering, and material lifetime. Four quantitative screening elements are introduced: an annualized capacity relation separating storage capacity from fill time; a mass-normalized carbon-intensity ceiling constraining embodied burden; a climate-operability state space based on experimentally validated thermal-humidity cycles; and timescale ratios requiring capture and transfer kinetics to fit within naturally available dry and wet periods. Five core hypotheses test collector performance, bounded climatic operation, interlayer carbon transfer, architectural advantage, and durable net removal. The framework requires environmental vetoes and predefined failure thresholds. It is intended not as a replacement for engineered direct air capture, but as a testable route toward complementary distributed carbon removal using existing surface area and naturally occurring environmental gradients.

INTRODUCTION

Carbon dioxide removal (CDR) is increasingly discussed as a complement to deep emissions reduction, particularly for residual emissions that are difficult to eliminate. Direct air capture (DAC) is attractive because it removes CO₂ directly from ambient air and is not tied to a point source. Its defining difficulty is the low atmospheric CO₂ concentration: a large quantity of air must interact with a selective material, and the captured carbon must subsequently be released, concentrated, or otherwise transferred into a durable storage pathway. The energy and material inputs of the full process, together with the final fate of the captured CO₂, determine whether a DAC system produces net-negative emissions (Erans et al., 2022).

This paper starts from a deliberately narrow systems question. If some of the functions normally provided by a dedicated DAC plant can be supplied by resources that already exist — exposed building area, wind-driven air contact, solar heating, nocturnal cooling, humidity changes, dew, and rain — can a useful fraction of atmospheric CO₂ removal be achieved with little additional *operational* energy? The question does not imply that passive systems are energy-free. Raw materials, manufacturing, application, maintenance, renewal, and end-of-life all carry environmental burdens and must be included in a conservative life-cycle balance. Nor is the proposed approach intended to replace engineered DAC. It is investigated as a potentially

complementary pathway whose usefulness would arise from distributed deployment over already existing surfaces rather than from high removal intensity per unit area.

Several elements of this idea are established independently. Moisture-swing sorbents can capture CO₂ under drier conditions and release it when water activity increases (Wang et al., 2011, 2013). Recent work has shown that pore architecture, counterions, polymer chemistry, and relative humidity strongly affect capacity and kinetics in moisture-swing materials (Hegarty et al., 2026; Mao et al., 2026). Passive or nature-assisted DAC has also been demonstrated at the device level. Filahi et al. (2025), for example, field-tested a passive adsorptive DAC concept driven by diurnal temperature differences. Existing infrastructure can likewise be used as an air-contact resource, as demonstrated by rooftop HVAC-integrated DAC modules (An et al., 2024), while architectural studies have begun to examine passive airflow as a design variable for building-integrated carbon-capture enclosures (Alam & Abbasabadi, 2026).

Mineral carbonation provides a different function: durable carbon fixation. Ca- and Mg-bearing phases can convert CO₂ to carbonate, but conversion is governed by humidity, temperature, microstructure, diffusion, and passivation (Zhang et al., 2026). Water films can both enable mineralization and generate self-limiting surface products; MgO experiments show a strong sensitivity to water-film thickness and progressive blocking of reactive surfaces (Luong et al., 2023).

Direct mineral carbonation has also been proposed and experimentally demonstrated in air contactors based on $\text{Ca}(\text{OH})_2$ (Criado et al., 2025).

Crucially, neither roof-based carbon uptake nor carbon-capturing coatings are new categories. Carbonating coatings based on reactive calcium silicates have been reported for concrete (Peng et al., 2023; Liang et al., 2025), and patent literature describes roofing or siding surfaces incorporating olivine or serpentinite granules intended to absorb atmospheric CO_2 over the service life of the surface (Finley & Geyer, 2024). These precedents mean that the contribution of *Passive Carbon Skin* cannot legitimately be framed as “the first carbon-capturing roof coating.”

The contribution proposed here is narrower and more falsifiable: a retrofit, spatially separated capture–transfer–mineralization architecture in which (i) an air-exposed layer provides reversible atmospheric capture, (ii) naturally occurring thermal and humidity transitions are treated as process variables that may drive transfer, and (iii) a distinct mineral reservoir provides the intended durable sink. The framework further couples that architecture to closed carbon accounting, building-physics constraints, environmental vetoes, and predefined failure criteria. A targeted, non-systematic literature and patent scan for this manuscript did not identify a peer-reviewed demonstration of this complete combination. This is not an exhaustive novelty or patentability claim; it defines the specific research gap addressed by the framework.

The central research question is therefore:

Can existing mineral building surfaces use naturally occurring thermal and humidity cycles to support a spatially separated CO_2 capture–transfer–mineralization process with sufficiently low additional operational energy and sufficiently favorable life-cycle accounting to justify experimental development?

The paper makes five methodological contributions. First, it defines the proposed system boundary and functional architecture. Second, it separates stoichiometric storage capacity from the rate at which that capacity can be used. Third, it derives both an areal carbon-budget ceiling and a mass-normalized coating carbon-intensity threshold. Fourth, it converts climatic intuition into measurable thermohygroscopic states and explicit timescale requirements for passive capture and transfer. Fifth, it translates the concept into falsifiable hypotheses and a validation sequence designed to produce either a reproducible development route or a robust negative finding.

LITERATURE REVIEW

DAC energy and the use of environmental process drivers

The thermodynamic and engineering challenge of DAC is not only sorbent affinity. Air handling, regeneration, working capacity, material stability, and downstream storage all contribute to system performance. Reviews of DAC consistently emphasize that energy and material inputs must be evaluated together rather than treating maximum equilibrium uptake as the decisive metric (Erans et al., 2022; Filahi et al., 2025). The present concept adopts the same systems view but asks whether part of the operational work can be displaced by environmental drivers.

There is clear precedent for this direction. Filahi et al. (2025) demonstrated a Passive Adsorptive Direct Air Capture (PADAC) device using natural day/night temperature differences to drive adsorption and desorption. Their work is particularly relevant because it establishes that naturally available thermal gradients can be treated as a legitimate DAC process resource rather than merely as an environmental disturbance. However, PADAC is a cyclic adsorptive device that produces a desorbed CO_2 stream; it does not propose a

spray-applied building-envelope architecture in which released or transferred carbon is immobilized in a separate mineral layer.

An et al. (2024) took a different route by integrating sorbent modules with existing rooftop HVAC equipment, thereby exploiting air movement that already occurs for another purpose. This supports the broader systems argument that existing infrastructure can provide valuable air-contact functionality. It remains an engineered sorbent module with a regeneration requirement and is therefore distinct from the proposed passive surface pathway.

Moisture-swing capture

Moisture-swing capture provides a mechanistic basis for reversible capture without conventional high-temperature regeneration. Wang et al. (2011) demonstrated quaternary-ammonium anion-exchange materials that absorb CO_2 when dry and release it upon wetting. Their subsequent thermodynamic analysis linked the swing to coupled H_2O – CO_2 –resin equilibria and the activity of water (Wang et al., 2013).

Recent research substantially sharpens this mechanism. Hegarty et al. (2026) showed that moisture-swing performance depends on pore architecture, functional group chemistry, counterions, water uptake, and relative humidity. A 2026 critical review similarly identifies humidity sensitivity, mass-transfer limitations, material shaping, stability, and cycle design as central unresolved issues (Mao et al., 2026). These findings argue against treating humidity as a binary switch. For an outdoor coating, the relevant variable is a bounded thermohygroscopic operating window in which capture, release/transfer, water transport, and pore reopening all remain compatible.

Mineral fixation, humidity, and passivation

Mineral carbonation can create durable carbonate phases, but practical performance depends on more than stoichiometric capacity. Zhang et al. (2026) synthesize extensive evidence that Ca- and Mg-based precursors differ in kinetics, products, humidity sensitivity, and passivation behavior. Ca-rich phases can react relatively quickly yet become diffusion-limited as carbonate products accumulate. Mg-rich systems can offer favorable theoretical capacity but often require careful management of hydration, nucleation, and passivating surface layers.

The role of nanometric water films is especially relevant to the proposed transfer layer. Luong et al. (2023) showed that Mg carbonate formation on MgO nanocubes is strongly controlled by water-film thickness, while accumulating carbonate can block continued access to the reactive core. This provides both mechanistic support and a warning: ambient humidity can enable mineralization, but repeated natural wet/dry cycling does not automatically guarantee continued sink utilization.

Criado et al. (2025) experimentally demonstrated atmospheric CO_2 capture with structured $\text{Ca}(\text{OH})_2$ solid forms in an air contactor, confirming that direct mineral reaction at DAC concentrations can be practically measurable. That approach uses the mineral phase itself as the active contactor. Passive Carbon Skin instead proposes that the air-contact and final mineral-sink functions may be separated to reduce near-surface passivation and preserve gas accessibility.

Building-surface and coating prior art

The use of building surfaces for carbon capture has relevant precedents. Peng et al. (2023) developed a carbon-capture coating based on CO_2 -activated dicalcium silicate for concrete, combining sequestration with durability enhancement. Liang et al. (2025) further developed a $\gamma\text{-C}_2\text{S}$ -based carbon-capture coating incorporating styrene-acrylic copolymer latex. These systems demonstrate that carbonatable functional coatings on construction materials are

technically credible research objects. Their principal mechanism is direct carbonation of the coating material itself, rather than reversible capture followed by climate-mediated transport to a separate reservoir. Patent prior art is even closer to the surface-area proposition. Finley and Geyer (2024) describe roofing and siding materials coated with olivine- and/or serpentinite-containing granules intended to absorb atmospheric CO₂ over the service life of a roof or siding system. This establishes that the idea of exploiting large existing building surfaces for direct mineral CO₂ uptake predates the present framework. Accordingly, the novelty boundary must be drawn at the coupled functional architecture and its validation logic, not at the use of roof area itself. Table 1 summarizes the nearest adjacent approaches identified in the targeted scan.

Table 1. Adjacent approaches and the specific boundary of the proposed contribution. 2.5 Evidence-status discipline

Adjacent approach	Established contribution	Distinction from the present framework
Moisture-swing sorbents (Wang et al., 2011, 2013; Hegarty et al., 2026)	Reversible capture controlled by water activity and sorbent structure	No integrated mineral sink on an existing building surface
PADAC (Filahi et al., 2025)	Nature-assisted thermal swing and field-tested passive adsorption/desorption	Device-level cyclic capture; desorbed CO ₂ still requires downstream handling
Rooftop HVAC DAC (An et al., 2024)	Uses existing rooftop infrastructure and pre-existing air movement	Engineered module with sorbent regeneration; not a passive coating/mineral sink
Passive enclosure CFD (Alam & Abbasabadi, 2026)	Architectural geometry and passive airflow treated as capture-relevant variables	Airflow framework; no demonstrated capture-transfer-mineralization chemistry
Ca(OH) ₂ air contactor (Criado et al., 2025)	Direct atmospheric mineral carbonation in a designed contactor	Mineral itself is the air-contact medium; no separated collector/transfer layer
Carbon-capture concrete coatings (Peng et al., 2023; Liang et al., 2025)	Reactive carbonating coatings on building materials	Direct carbonation/densification; no reversible collector feeding a separate sink
Olivine/serpentinite roof/siding patent (Finley & Geyer, 2024)	Uses roof/siding surface area for direct mineral atmospheric CO ₂ uptake	Direct exposed-mineral weathering; no cyclic collector-to-reservoir transfer architecture

Because no experimental data for Passive Carbon Skin are presented here, the manuscript uses four evidence categories:

1. Established basis: mechanisms or empirical results supported by cited literature.
2. Theoretical proposition: a proposed coupling, architecture, or mathematical screening relation introduced in this study.
3. Illustrative scenario: a numerical input chosen to examine sensitivity; it is not a prediction.
4. Proposed validation: an experiment or decision rule intended to test the proposition.

This distinction is essential. Terms such as “capture,” “transfer,” and “mineralization” describe intended functions of the architecture, not experimentally demonstrated performance of the proposed coating.

MATERIALS AND METHODS

This study is theoretical and methodological. No Passive Carbon Skin material was synthesized or tested for this manuscript. The starting architecture and illustrative baseline are taken from an earlier public R&D proposal (Author, 2026), while the present paper adds literature/prior-art positioning, explicit theoretical screening equations, a climate-operability formalism, timescale constraints, and a compressed validation design.

To position the contribution, a targeted, non-systematic scan considered peer-reviewed literature and openly accessible patent records using combinations of terms related to direct air capture, moisture swing, passive or nature-assisted DAC, building-integrated DAC, carbon-capture coatings, roof mineralization, mineral carbonation, and climate-driven capture. The scan was used to identify adjacent approaches and refine the novelty boundary; it is not a systematic review, a patentability opinion, or a freedom-to-operate analysis.

Functional architecture

The proposed architecture separates four functions:

- **K — air-contact / collector layer:** open gas access and reversible CO₂ capture;
- **T — transition zone:** short-path transport during an appropriate moisture/thermal state;
- **S — mineral reservoir:** conversion of transferred inorganic carbon into a durable mineral phase;
- **P — adhesion / decoupling layer:** substrate compatibility, renewability, and preservation of building physics.

The existing clay tile, concrete tile, or mineral facade is treated as the carrier rather than as a sacrificial carbon sink. Figure 1 shows the conceptual arrangement.

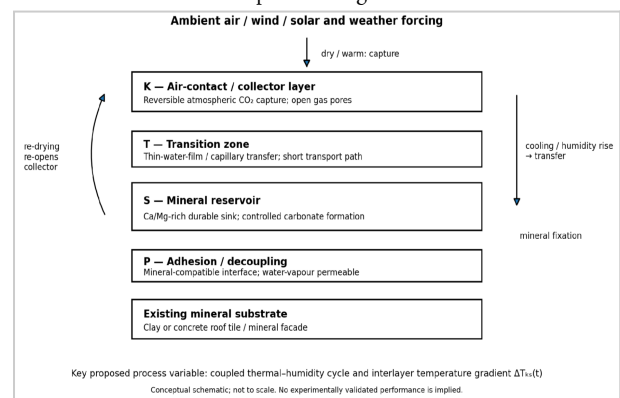


Figure 1. Conceptual Passive Carbon Skin architecture and proposed climate-driven process sequence.

The intended cycle is: (1) capture under a favorable air-contact state; (2) a thermal/humidity transition that changes collector affinity and enables connected thin water films; (3) transfer toward the mineral reservoir; (4) mineral fixation; and (5) re-drying that reopens the collector layer. The framework does not assume that carbon will move inward merely because the layers are stacked vertically. Directional transfer must arise from a measurable chemical-potential or concentration gradient, capillary connectivity, and a sufficiently

reactive mineral sink that removes dissolved inorganic carbon from the transition zone. If collector release predominantly returns CO₂ to ambient air, the architecture fails its central transfer hypothesis. The critical proposition is that natural environmental cycling can perform enough of these state transitions to make active fan- or heat-driven regeneration unnecessary during normal operation. This proposition is invalidated.

Closed carbon balance

A credible CDR claim requires a closed carbon pathway. For an areal test element and a defined test interval, let cumulative atmospheric CO₂ uptake entering the coating system be represented by

$$m_{atm,in} = \Delta m_K + \Delta m_S + m_{run} + m_{rel} + \varepsilon$$

The terms on the right-hand side represent, respectively, the change in collector-layer carbon inventory, the change in mineral-sink carbon inventory, carbon leaving in runoff, carbon returned to the air, and measurement uncertainty or any unclosed fraction. For this physical carbon balance, all terms are reported on an equivalent CO₂-mass basis; measured carbon quantities are converted stoichiometrically to corresponding CO₂ mass. This is distinct from life-cycle CO₂-equivalent emissions (CO₂e), which enter the net-removal assessment separately. Durable removal can be credited only to carbon that remains in a verified storage phase after washing, re-drying, and aging.

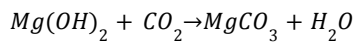
Stoichiometric storage ceiling

For a mineral sink material *S*, a generic areal stoichiometric storage ceiling can be written as

$$C_{st} = m_s \frac{v_{CO_2} M_{CO_2}}{M_s}$$

where m_s is the installed reactive sink mass per unit area, M_s is its molar mass, and v_{CO_2} is the number of moles of CO₂ incorporated per mole of sink material under the assumed reaction.

For the illustrative reaction



the ideal mass ratio is approximately

$$\frac{M_{CO_2}}{M_{Mg(OH)_2}} \approx 0.755.$$

Thus, the baseline value $m_{Mg(OH)_2} = 0.180 \text{ kg m}^{-2}$ yields

$$C_{st} \approx 0.136 \text{ kg CO}_2 \text{ m}^{-2}.$$

This is a storage ceiling, not a performance prediction. It contains no kinetics and says nothing about whether ambient carbonation proceeds on a useful timescale.

Capacity utilization and fill time

A principal limitation of capacity-only reasoning is that it hides time. Let U_s denote the fraction of the stoichiometric reservoir that is actually and durably utilized during one fill/renewal interval, with $0 \leq U_s \leq 1$. Let τ_f be the time required to reach that retained utilization. A first-order annualized gross screening flux is then

$$J_{gross} = \frac{C_{st} U_s}{\tau_f}.$$

J_{gross} has units of mass CO₂ per area per time. This equation makes explicit that a high storage ceiling is not useful if the reservoir fills only over very long periods, while a modest capacity can become relevant if it is repeatedly and safely renewed. No value of U_s or τ_f is claimed here; both are empirical quantities.

Carbon-budget ceiling for net removal

The modest areal storage ceiling creates a stringent life-cycle constraint. Let e_{LCA} be the cradle-to-end-of-life CO₂-equivalent burden allocated to one square metre over a fill/renewal interval. Let m_{rel} and m_{run} represent carbon lost by re-release and runoff during the same interval. An annualized net screening relation is

$$J_{net} = \frac{C_{st} U_s - m_{rel} - m_{run} - e_{LCA}}{\tau_f}.$$

A necessary condition for net-negative operation is therefore

$$e_{LCA} < C_{st} U_s - m_{rel} - m_{run}.$$

This inequality is one of the most restrictive design consequences of the framework. At the 136 g CO₂ m⁻² stoichiometric ceiling, even a seemingly modest embodied-carbon burden can eliminate the entire removal benefit. The framework therefore treats low-carbon materials, low-loss application, durability, renewability, and end-of-life as entry conditions rather than optimization details.

Mass-normalized coating carbon-intensity threshold

The same carbon-budget constraint can be expressed per unit mass of applied dry coating. Define the dry coating mass per unit area and the cradle-to-end-of-life carbon intensity of the complete coating system, including the allocated burdens of the collector, mineral sink, binder, processing, transport, application, maintenance, renewal, and end-of-life. The maximum compatible mass-normalized intensity before other unallocated losses is

$$I_{coat,max} = \frac{C_{st} U_s - m_{rel} - m_{run}}{m_{coat}}$$

For the illustrative baseline dry mass of 400 g m⁻², this threshold is only 102, 170, 238, and 340 g CO₂e kg⁻¹ dry coating at durable utilizations of 0.30, 0.50, 0.70, and 1.00, respectively, before additional re-release or runoff losses. These are not life-cycle estimates; they are break-even ceilings. The relation provides a direct material-screening rule: a high-embodied-carbon collector or binder can invalidate the CDR case even if the coating carbonates successfully.

Thermohygroscopic operating state

The initial proposal treated day/night temperature and humidity cycling as environmental drivers. The present framework makes that proposition more explicit. Define the instantaneous interlayer temperature difference as

$$\Delta T_{KS}(t) = T_K(t) - T_S(t),$$

where T_K is the temperature of the air-contact/collector region and T_S is the temperature of the storage region or its immediately coupled substrate.

For each identifiable environmental cycle *i*, define a state vector

$$c_i = (\Delta T_{KS,i}, RH_{min,i}, RH_{max,i}, \tau_{dry,i}, \tau_{wet,i}, v_{air,i}),$$

where RH is relative humidity, τ_{dry} and τ_{wet} are durations of the dry and wet portions of the cycle, and v_{air} is near-surface air velocity or another validated air-contact metric.

Laboratory testing is used to identify an experimentally admissible operating region Ω in this state space. A site-specific *cycle operability fraction* can then be defined as

$$\Phi_{\Omega} = \frac{1}{N} \sum_{i=1}^N I(c_i \in \Omega),$$

where I is the indicator function. Φ_{Ω} is not an efficiency and not a CO_2 -removal prediction. It is a proposed screening metric: the fraction of observed environmental cycles that fall within a laboratory-validated operating window. It replaces broad geographic assumptions such as “warm climates should perform better” with a testable pathway based on actual surface-temperature, humidity, wetting, drying, and wind data.

Timescale compatibility and cycle-to-site translation

A thermohygrometric cycle can be geographically available yet kinetically useless. Let the characteristic capture-loading time describe meaningful collector loading under the dry/capture state, and let the characteristic transfer time describe measurable interlayer transfer under the wet/transition state. Define two dimensionless timescale-compatibility ratios as

$$R_{cap} = \frac{\tau_{dry}}{\tau_{cap}}, \quad R_{tr} = \frac{\tau_{wet}}{\tau_{tr}}$$

A necessary, though not sufficient, condition for productive passive cycling is

$$R_{cap} \geq 1, \quad R_{tr} \geq 1, \quad \tau_{redry} < \tau_{cycle}$$

These inequalities do not predict performance; they state a timing requirement. If capture is slower than the available dry interval, if transfer is slower than the connected wet interval, or if re-drying cannot restore gas access before the next cycle, natural weather variability cannot substitute for active process control. Once laboratory testing provides a measured durable retained-carbon increment as a function of validated cycle state, site data can be translated into an annualized areal rate through

$$J_{site}(T) = \frac{1}{T} \sum_{i=1}^{N(T)} q_{ret}(c_i) 1_{\Omega}(c_i)$$

In this relation, the retained-carbon increment is the measured durable increment per area for each cycle state; the indicator function equals one inside the validated operating region and zero outside it; the summation covers the identifiable cycles in observation period T . The resulting site rate remains contingent on field verification. This formulation prevents the climate-operability fraction from being mistaken for a capture efficiency.

Area scaling

If an experimentally established net areal rate J_{net} becomes available, the surface area required for a target annual removal M_{target} follows directly:

$$A_{req} = \frac{M_{target}}{J_{net}}.$$

Before life-cycle data exist, J_{gross} can be used only for gross sensitivity analysis, never for a CDR claim.

RESULTS AND DISCUSSION

Capacity, utilization, and time cannot be conflated

For the illustrative $\text{Mg}(\text{OH})_2$ baseline, the stoichiometric ceiling is approximately $136 \text{ g CO}_2 \text{ m}^{-2}$. Table 2 evaluates generic utilization fractions and fill times solely to show the scale of the problem. The utilization values are scenario inputs, not expected efficiencies and not assigned to any geography.

Table 2. Illustrative gross areal rates for a $136 \text{ g CO}_2 \text{ m}^{-2}$ storage ceiling. Values are sensitivity scenarios, not predicted performance. The calculation

Utilized fraction U_s	Fill time τ_f (yr)	Gross rate ($\text{g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$)	Gross rate ($\text{t CO}_2 \text{ km}^{-2} \text{ yr}^{-1}$)	Area for 1 Mt CO_2 yr^{-1} , gross only (km^2)
0.30	1	40.8	40.8	24,510
0.50	1	68.0	68.0	14,706
0.70	1	95.2	95.2	10,504
0.50	3	22.7	22.7	44,118
0.50	5	13.6	13.6	73,529
1.00	1	136.0	136.0	7,353

provides two immediate conclusions. First, the concept is intrinsically area-intensive; its potential rationale is the availability of already existing surface area, not high removal density. Second, fill time is at least as important as storage capacity. A coating that ultimately stores half of its theoretical capacity over five years has one fifth of the annualized gross flux of a coating reaching the same utilization in one year.

The same relation can be inverted to define a maximum permissible fill time for a chosen gross areal-rate target J^* :

$$\tau_{f,max} = \frac{C_{st} U_s}{J^*}$$

For example, at 50% durable utilization of the illustrative reservoir, sustaining $50 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$ gross would require a fill time no longer than approximately 1.36 years; $100 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$ would require approximately 0.68 years. These values are not targets endorsed by the framework; they expose the kinetic burden that any experimentally observed system must satisfy.

The life-cycle carbon budget is unusually tight

Before re-release or runoff losses are considered, the maximum allowable life-cycle burden per square metre is bounded by $C_{st} U_s$. For the illustrative storage ceiling, the gross carbon-budget ceilings are shown in Table 3.

Table 3. Break-even life-cycle carbon ceilings for the illustrative 400 g m^{-2} dry-coating baseline. Values exclude re-release and runoff losses.

Utilized fraction, U_s	Gross retained capacity ($\text{g CO}_2 \text{ m}^{-2}$ per fill interval)	Maximum life-cycle burden before other losses ($\text{g CO}_2 \text{ e m}^{-2}$)
0.30	40.8	< 40.8
0.50	68.0	< 68.0
0.70	95.2	< 95.2
1.00	136.0	< 136.0

Table 4. Mass-normalized break-even coating carbon intensity for the illustrative 400 g m⁻² dry-coating baseline. Values exclude re-release and runoff losses.

Utilized fraction, U_s	Maximum coating carbon intensity before other losses (g CO ₂ e kg ⁻¹ dry coating)
0.30	< 102
0.50	< 170
0.70	< 238
1.00	< 340

This result is more consequential than the headline stoichiometric capacity. It means that a carbon-capturing coating can fail as CDR even when it chemically fixes CO₂ successfully. If raw-material production, functionalization, transport, spray application, maintenance, renewal, or disposal consumes a comparable carbon budget, there is no net removal. Table 4 makes the mass-normalized constraint especially visible: at 50% durable utilization, the complete 400 g m⁻² dry coating must remain below 170 g CO₂e kg⁻¹ before any re-release or runoff is counted. Because those losses further reduce the allowance, the practical threshold is lower.

The theoretical framework therefore places the life-cycle burden *upstream* in the material-screening process. High capture performance cannot rescue a formulation with an unfavorable carbon footprint or unacceptable environmental release.

The coating-mass budget constrains material complexity

The mass-normalized ceiling creates a direct design implication. The illustrative baseline cannot tolerate a high-carbon functional layer simply because that layer is thin or highly selective. Every added component consumes part of a small areal carbon budget. At 50% durable reservoir utilization, the gross break-even allowance is 68 g CO₂e m⁻², equivalent to 170 g CO₂e kg⁻¹ of the full 400 g m⁻² dry system before other losses. If the mineral base, binder, preparation, and application already consume most of this allowance, only a very small residual budget remains for collector functionalization.

This suggests a screening hierarchy that differs from conventional sorbent optimization: first reject formulations whose plausible embodied burden cannot fit within the theoretical carbon budget; only then optimize capture capacity, selectivity, and cycle kinetics. A future prospective life-cycle inventory should therefore report the carbon contribution of each layer separately and calculate the residual budget available to the collector chemistry.

Passive cycling requires timescale matching

The environmental state-space is useful only if the material kinetics fit inside the available weather intervals. A roof can experience a favorable humidity transition every day and still produce negligible carbon removal if collector loading requires several days, interlayer transfer requires longer than the connected water film persists, or the coating remains wet and gas-blocked after the transition. The two timescale-compatibility ratios therefore act as necessary kinetic gates. Their values are conceptual rather than predictive until the characteristic capture and transfer times are measured, but they define the quantities that a climate-chamber program must extract before geographic deployment can be discussed quantitatively.

This timescale view also clarifies the role of temperature gradients. A thermal gradient is useful only insofar as it changes affinity, water-film formation, transport, or drying on a timescale compatible with the cycle. Large absolute temperature swings are not intrinsically beneficial. The relevant experimental question is whether the coupled thermal and humidity trajectory crosses a productive state sequence often enough and for long enough to complete capture, transfer, and

reset.

The proposed climate metric avoids unsupported geographic claims

The state-space metric Φ_Ω creates a route from laboratory science to geographic applicability without assuming that latitude or average air temperature alone controls performance. A site with large daily temperature swings but insufficient humidity transition could be unsuitable; a humid site could likewise remain outside the operating region if the collector never re-dries sufficiently. Conversely, a site with moderate temperatures could provide many productive cycles if surface heating, nocturnal cooling, dew formation, and drying repeatedly cross the validated window.

The key consequence is methodological: climate suitability should ultimately be mapped from surface-level cycle data evaluated against a measured operating region, not assigned a priori by continent or climate label. This provides a direct way to test the working intuition that thermal gradients matter strongly while preventing that intuition from being reported as an established performance relationship.

Added value of the framework

The analysis above converts the original concept into six quantitative gates that can be evaluated before scale-up:

1. Storage gate: Is the stoichiometric storage ceiling large enough to justify the coating mass and renewal strategy?
2. Rate gate: Are durable utilization and fill time sufficient to produce a relevant annualized areal flux?
3. Material-carbon gate: Can the full coating and its maintenance remain below the mass-normalized break-even carbon-intensity ceiling with a defensible margin?
4. Timescale gate: Do capture, transfer, and re-drying complete within naturally available cycle intervals?
5. Climate-state gate: Does the target site provide enough validated cycles within Ω ?
6. Net-carbon gate: Is the life-cycle burden comfortably below retained mineral carbon after re-release and runoff are included?

A candidate that fails any one of these gates is not a CDR candidate, even if its isolated laboratory uptake appears attractive.

Falsifiable hypotheses and experimental validation pathway

The public proposal contained ten development hypotheses. For a journal manuscript, they are compressed into five core hypotheses that directly test the coupled architecture.

H1 — Collector effect

Hypothesis. At least one immobilized collector formulation produces reproducibly greater atmospheric carbon uptake than composition-matched non-collector controls under identical air-contact conditions.

Primary comparison. Collector variant versus uncoated substrate, binder/pore-carrier blank, and porous mineral matrix without active collector.

Failure condition. No statistically and analytically meaningful retained uptake above controls under sufficient exposure time.

H2 — Bounded thermohygrometric operating window

Hypothesis. Durable cyclic transfer is maximized within a bounded thermal-humidity operating region rather than under permanently dry or permanently wet conditions.

Primary variables. Interlayer temperature difference, minimum/maximum RH, wet-film duration, dry-out duration, near-surface air velocity, cycle frequency, characteristic capture time, characteristic transfer time, and re-drying time.

Validation logic. A climate chamber should impose a matrix of predeclared thermal and humidity cycles, including dry controls, persistently humid controls, temperature-only cycles, humidity-only

cycles, and combined cycles. The purpose is not initially to emulate a specific city, but to identify the operating region Ω .

Failure condition. No cycle-dependent benefit, no repeatable operating region, or performance dependent on conditions unlikely to occur on exposed surfaces.

H3 — Interlayer carbon transfer

Hypothesis. During productive transition cycles, carbon associated with the collector layer decreases while analytically confirmed inorganic carbon in the mineral reservoir increases, within a closed carbon balance.

Measurements. Gas-phase CO_2 inlet/outlet, inorganic carbon in each layer, runoff carbon, re-release during re-drying, and mineral-phase analysis by XRD/FTIR or an equivalent validated method.

Failure condition. The collector releases CO_2 but the mineral layer shows no corresponding carbon gain, or the mass balance closes primarily through re-release/runoff.

H4 — Architectural advantage

Hypothesis. A spatially separated or gradient architecture retains more durable CO_2 over repeated cycles than a homogeneous mixture with the same total active components.

This is the central systems claim. Direct mineral coatings already exist in the literature. Passive Carbon Skin is scientifically useful only if functional separation produces a measurable advantage, such as improved gas access, delayed passivation, higher retained fraction, faster re-drying, or better compatibility with the substrate.

Failure condition. A homogeneous or direct-mineral control performs equally well or better after normalization for material mass, exposure, and carbon balance. In that case the added complexity of the layered architecture is not justified.

H5 — Durable net removal under environmental and building constraints

Hypothesis. At least one frozen formulation can retain analytically verified mineral carbon after washing, re-drying, and accelerated aging while maintaining a conservatively positive net carbon balance, remaining below the applicable coating carbon-intensity ceiling, and passing environmental/building-physics vetoes.

Required vetoes. No progressive problematic leaching, persistent particle release, unacceptable runoff effects, major loss of adhesion, delayed substrate drying, large reduction in water-vapour transmission, or freeze/moisture damage attributable to the coating.

Failure condition. Gross uptake is positive but life-cycle burden, re-release, runoff, material loss, environmental harm, or building damage makes $J_{\text{net}} \leq 0$ or otherwise invalidates deployment.

In addition to structural and environmental failure modes, secondary mineral precipitation may produce efflorescence, discoloration, surface roughening, or other visible alterations. Such effects may not directly invalidate carbon retention, but they could render a formulation unsuitable for architectural deployment and should therefore be included among practical building-envelope veto criteria.

Minimum experimental sequence

A first validation program should be deliberately small and discriminating rather than attempting product optimization.

Stage 1 — Baseline characterization. Confirm starting mineral phases, carbon background, particle size, porosity, coating mass, adhesion, water-vapour behavior, and collector chemistry.

Stage 2 — Controlled coupon matrix. Use coded replicates of uncoated substrate, binder blank, mineral-only baseline, homogeneous active mixture, layered/gradient architecture, and collector variants. Randomize sample position in the climate chamber and blind at least one analytical evaluator to material codes.

Stage 3 — Operating-window mapping. Vary temperature and humidity cycles systematically. Measure both surface and internal layer temperatures rather than relying on chamber air temperature alone. Identify whether a reproducible Ω exists.

Stage 4 — Carbon-pathway closure. Quantify gas-phase carbon, layer-specific inorganic carbon, runoff, and re-release. Credit only carbon that is analytically located in the intended durable sink after washing and re-drying.

Stage 5 — Repetition and aging. Repeat productive cycles sufficiently to detect decay in uptake/transfer rate, pore blockage, passivation, adhesion loss, and collector degradation. The exact cycle count should be defined before data inspection.

Stage 6 — Frozen-formulation test. Once a candidate is selected, freeze composition, layer thickness, application method, environmental thresholds, and endpoints before confirmatory testing. Parameter changes after failure constitute a new version and new experiment rather than a rescue of the original hypothesis.

First field transition: from chamber to roof tile

Only after a laboratory operating window has been measured should meteorological deployment be considered. The first field step should use instrumented individual roof tiles or small modules rather than a full roof. Required measurements include air and surface temperature, temperature through the coating/substrate, RH, surface wetness, precipitation, wind, re-drying time, runoff chemistry, and removable analytical coupons. These data can then be transformed into the cycle vectors c_i used to calculate Φ_Ω .

This sequence prevents a common scale-up error: using weather data to predict performance before the relevant material operating window is known.

What the concept does and does not claim

The present framework does not demonstrate a functioning carbon-removing coating. It demonstrates that the proposal can be stated in a form that is quantitatively bounded and experimentally falsifiable. That distinction matters because all three underlying process classes — reversible air capture, climate-driven cycling, and mineral carbonation — have strong dependencies on material chemistry and local conditions.

The intended value proposition is therefore not high areal intensity. Even the illustrative upper bound of $136 \text{ g CO}_2 \text{ m}^{-2}$ per reservoir fill is modest relative to industrial CDR throughput. The proposed advantage, if any, would arise from three properties: existing surface area, low incremental operational energy, and distributed deployment. Table 2 shows that this argument also creates an immediate burden of proof: very large surface areas are needed for megaton-scale gross removal unless fill times are short or reservoir capacity increases materially.

Why functional separation may matter

Direct mineral carbon-capture coatings and mineralized roof surfaces already provide a simpler path to surface-based CO_2 uptake. A separated architecture is justified only if it solves a real limitation. The most plausible candidates are (i) maintaining an air-open capture interface while carbonation occurs deeper in the coating, (ii) reducing near-surface passivation, (iii) allowing the capture chemistry and mineral sink to be optimized independently, and (iv) using transient thin water films for transport without keeping the gas-contact layer permanently flooded.

These advantages remain hypotheses. In fact, prior research creates strong reasons to expect failure modes. Moisture-swing materials can suffer slow kinetics and humidity sensitivity (Hegarty et al., 2026; Mao et al., 2026). Mineral phases can passivate or carbonate too slowly under ambient conditions (Luong et al., 2023; Zhang et al.,

2026). A transition layer can become a diffusion barrier instead of a transport pathway. The roof substrate can retain water for too long or lose vapor permeability. Any of these effects could remove the expected advantage of functional separation.

Temperature gradient as a process variable

A central extension in this paper is the explicit treatment of the interlayer thermal gradient $\Delta T_{KS}(t)$ and thermohygroscopic cycle as process variables. Natural temperature swing has already been shown to drive passive adsorption/desorption in a dedicated DAC device (Filahi et al., 2025), but the relevant gradient in a thin building coating is not necessarily identical to ambient day/night temperature range. Solar absorptivity, emissivity, wind, roof orientation, substrate thermal inertia, coating thickness, moisture content, and night-sky cooling can all alter the surface-to-reservoir temperature history.

The practical consequence is that “warm climate” and “large day/night swing” are insufficient descriptors. The physically relevant question is whether the coating experiences repeatable sequences that (1) permit capture, (2) produce the necessary affinity/transport transition, and (3) return the surface to an open, capture-capable state. Measuring $\Delta T_{KS}(t)$ and calibrating Ω provides a way to resolve this empirically.

Why the carbon-budget ceiling may be the hardest constraint

The most sobering result of the theoretical screening is the life-cycle ceiling. At a $136 \text{ g CO}_2 \text{ m}^{-2}$ maximum reservoir capacity, a 50% durable utilization permits less than $68 \text{ g CO}_2 \text{e m}^{-2}$ of life-cycle burden before any re-release or runoff loss is counted. For the illustrative 400 g m^{-2} dry coating, this corresponds to less than $170 \text{ g CO}_2 \text{e kg}^{-1}$ of finished coating. This is a demanding constraint for a multilayer functional material and may ultimately be more restrictive than the adsorption chemistry itself. It suggests that the concept is unlikely to succeed through chemically elaborate, high-embodied-energy collector phases or frequent whole-coating replacement.

This result also changes the material-design objective. The “best” collector is not necessarily the one with the highest short-term uptake. It is the one that contributes to the largest *net durable removal per unit of total life-cycle burden* while preserving the building function. Low-mass active layers, long service life, partial renewal, mineral-compatible processing, low-carbon feedstocks, and recovery/reuse may be more important than maximizing a single adsorption metric.

A further practical constraint is the relationship between mineralization kinetics and the service or renovation interval of the building envelope. If a functional coating is expected to remain in service for approximately 15–25 years, relatively slow ambient mineralization may still be compatible with deployment, provided that meaningful reservoir utilization occurs within that interval and that durable carbon retention, coating integrity, and a positive life-cycle balance are maintained. Conversely, if substantial utilization of the mineral reservoir requires timescales well beyond realistic maintenance or renovation cycles, the concept may remain chemically feasible while becoming practically irrelevant as a carbon-removal pathway. The relevant criterion is therefore not rapid carbonation alone, but sufficient durable utilization within the actual service life of the coating system.

Complementarity with engineered DAC

The framework should not be evaluated as a universal substitute for conventional DAC. Engineered DAC has advantages that a passive coating may never provide: controllable throughput, concentrated CO_2 output, process intensification, and the ability to site equipment

near dedicated storage or low-carbon energy. Passive Carbon Skin explores the opposite corner of the design space: low areal intensity, distributed contact, environmental driving forces, and direct mineral retention.

A meaningful outcome could therefore be limited but still useful. If empirical work finds a narrow class of climates, substrates, and formulations with positive net removal and long renewal intervals, the system could provide a supplementary distributed sink. If the kinetics, life-cycle budget, or building constraints fail, the framework still produces a useful negative result by identifying which coupling step is prohibitive.

This manuscript has substantial limitations that must remain explicit.

First, no Passive Carbon Skin formulation has been experimentally validated. All material compositions referenced from the public proposal are development baselines, not optimized products. Second, the $136 \text{ g CO}_2 \text{ m}^{-2}$ value is a stoichiometric upper bound for an illustrative $\text{Mg}(\text{OH})_2$ loading, not an expected field capacity. Third, the scenario values in Table 2 do not represent Europe, Africa, or any other geographic region; they are generic sensitivity inputs. Fourth, the functional relationship between temperature gradient, humidity cycling, collector affinity, interlayer transport, and mineralization is unknown. Fifth, ambient Mg-based carbonation may be kinetically slow and strongly affected by passivation. Sixth, the proposed Φ_Ω metric becomes useful only after the operating region Ω is established experimentally. Seventh, no prospective life-cycle inventory has yet been performed for the full coating, so the carbon-budget inequality identifies a requirement rather than demonstrating compliance. Eighth, the targeted prior-art search is not a systematic patentability or freedom-to-operate analysis and cannot support an absolute novelty claim. Finally, scalability from coupons to roof modules and long-term environmental safety remain untested.

CONCLUSIONS

Passive Carbon Skin is proposed as a falsifiable framework for testing whether existing mineral building surfaces can support a low-operational-energy atmospheric CO_2 capture–transfer–mineralization pathway. The concept deliberately separates reversible air contact from mineral storage and treats naturally occurring thermal and humidity cycles as process variables rather than background conditions.

The present analysis adds quantitative boundaries that were not explicit in the initial public R&D proposal. Stoichiometric capacity must be separated from fill time; the coating mass creates a stringent embodied-carbon intensity ceiling; passive cycling requires capture and transfer kinetics to fit within naturally available dry and wet intervals; and climate suitability should be defined by experimentally validated cycle states rather than geography. These constraints make clear that chemical uptake alone would be insufficient evidence of CDR.

The proposed architecture is scientifically justified only if experiments show an advantage over simpler controls, including direct mineral coatings and homogeneous mixtures. The next decisive step is therefore not further conceptual elaboration but a controlled coupon experiment that maps the thermohygroscopic operating window, closes the carbon balance, verifies interlayer transfer and mineral retention, and tests building and environmental vetoes. A negative result should be treated as informative: if nature does not support the coupled pathway, the framework should identify where and why it fails.

CONFLICTS OF INTEREST

The author declares no competing financial or non-financial interests related to this manuscript.

FUNDING

No external funding was received for this study.

DATA AVAILABILITY

No empirical dataset was generated for this theoretical and methodological study. Numerical values in the screening tables are derived from the equations and explicitly stated illustrative assumptions. The citation and record identifier for the earlier public R&D proposal are withheld from the review manuscript to preserve double-blind review.

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Spatial assessment of blue-green tourism potential and sustainable development priorities in the Central Aran economic region of Azerbaijan

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Keywords

*Blue-green tourism, Central Aran, GIS,
land-cover suitability, sustainable
tourism, water proximity*

ABSTRACT

Blue-green tourism provides prospects to merge water-based recreation opportunities, natural landscapes and sustainable regional development in places with not yet fully exploited tourism potential. Using GIS-based spatial suitability approach, this study evaluates the potential of blue-green tourism in the Central Aran economic region of Azerbaijan. The administrative boundaries, together with water features (OpenStreetMap) and land-cover data (ESA WorldCover 2021) were harmonised in a common projected coordinate system and processed using QGIS. In total, two main spatial indicators were created: water proximity suitability and green and natural land-cover suitability. Water proximity was assigned five suitability scores based on the distance to rivers, reservoirs and other water bodies and land-cover classes were reclassified using a tourism suitability scale of 5, based on the relative recreational and ecological value of tree cover, shrubland, grassland, cropland, built-up areas, sparse vegetation and wetlands. The results show a clear spatial clustering of high water-related suitability values along the Mingachevir Reservoir and along the Kura River corridor, and further local suitability values in proximity to secondary water features. Land-cover suitability exhibits a more geographically diverse pattern related to the agricultural, semi-natural and urbanised nature of the area. Overall, these spatial patterns suggest that there is a great potential for blue-green tourism development in Mingachevir, Yevlakh and Kura River corridor, while other districts need to be planned more carefully regarding landscape, infrastructure and recreational aspects. The results offer a territorial basis for prioritizing actions and investments for sustainable tourism in the region.

INTRODUCTION

Spatial planning approaches that balance natural resource and landscape functions with economic opportunity are now a greater need for tourism development. Recreational activities can be integrated within natural or semi-natural water bodies, riparian corridors, wetlands, vegetation and other natural or semi-natural land-cover elements, at the same time providing ecosystem services and environmental resilience in the region. This view suggests that the elements which are blue and green in the landscape should not be seen as isolated tourism resources but should be seen as spatial resources influencing one another in terms of their suitability for sustainable tourism development in terms of accessibility, ecological properties and surrounding land uses. It has also been shown that green infrastructure networks have a positive impact on recreation, human health and many other ecosystem services with a particular focus on the spatial dimension and at regional scale (Maes et al., 2015).

The spatial relationships can be effectively converted to measurable indicators by using geographic information systems (GIS). GIS-based tourism assessments have the ability to combine environmental resources, land cover, accessibility, infrastructure and other territorially differentiated factors in a common analytical environment. GIS-based multicriterion approaches are proven to be useful to determine spatial variation in rural tourism potential as well as to aid public and private investment decision-making (González-Ramiro et al., 2016). More

recent studies have also demonstrated the potential of GIS for sustainable destination planning with a focus on identifying underutilized tourism resources, visualizing spatial trends, and enhancing evidence-based decision-making (Šoltésová et al., 2025). Especially in Azerbaijan, where the variability of water resources, land-use pressure, and the general green-shift are increasingly influencing regional development priorities. Recent satellite-based studies have shown the value of combining hydrological and socioeconomic data to understand Azerbaijan's Caspian Sea and strategic inland water systems, such as exposure of economic activities to water changes (Qadimli et al., 2026). At the same time, India's shift towards more eco-friendly development will need better investment mechanisms, more societal involvement, as well as spatial and ecological assessment. Research on green finance in Azerbaijan has emphasized the role of financial instruments in promoting environmentally friendly investments (Sadiqov et al., 2026), and evidence on youths' knowledge and perceptions of green finance has shown the need for awareness and engagement in advancing the social aspect of the green transition (Mammadov, 2025). The same applies to sustainable tourism, where environmental assets have to be coupled with sustainable investment and development strategies in the region. An assessment for such a landscape is suitable in the Central Aran economic region as it includes significant water resources, agricultural territories, settlements, and a (semi-)natural and diverse landscape in terms of land cover. In particular, the Mingachevir Reservoir and the

Kura River system provide a significant blue spatial structure which, in combination with green and rural space around it, can be used to develop recreation and tourism opportunities. The purpose of this study is to spatially analyze the blue-green tourism potential in the Central Aran economy region of Azerbaijan by combining water proximity, green and natural land-cover characteristics, access indicators, the tourism infrastructure, and various socioeconomic indicators within a GIS-based framework and to determine territorially differentiated priorities to develop blue-green tourism.

LITERATURE REVIEW

The underlying concept of blue-green tourism is at the nexus of blue-space research, green infrastructure and nature-based recreation and sustainable tourism planning. Beyond their ecological value, rivers, lakes, reservoirs, wetlands and other blue spaces can offer recreation, aesthetics and other restorative functions. A systematic review by Gascon et al. (2017) revealed overall positive relations between exposure to outdoor blue spaces and mental well-being and physical activity; other meta-analytic studies have subsequently identified physical activity, restoration and social interaction as main routes by which blue spaces can create benefits for people (Georgiou et al., 2021). These results support the importance of water environments both as ecological resources and as environments that can be used to support recreation and visitors experiences.

Green infrastructure offers a complementary dimension, linking together the vegetation, semi-natural landscapes and ecosystem services, recreation and spatial quality. Ecosystem-service research (Maes et al., 2015) has a mature understanding of the recreational functions of green infrastructure. The relationship between blue and green landscape features can thus present diversified opportunities for nature observation, outdoor recreation, rural tourism and low-impact visitor activities from a tourism point of view. A spatial integrated analysis can better reflect the influence of geographical proximity and land-cover characteristics of water and terrestrial landscapes in the assessment of tourism suitability than the separate assessment of water and terrestrial landscapes.

To transform these environmental attributes into spatial tourism indicators, GIS has emerged as a valuable decision-support tool. For instance, Nino et al. (2017) integrated land cover, streams, roads, topography and natural attractions to identify ecotourism potential in Ethiopia, which showed that land-cover and landscape characteristics can be systematically incorporated into tourism suitability mapping. Similarly, Zabihi et al. (2020) integrated the GIS with fuzzy AHP method for physical, environmental and socioeconomic criteria in ecotourism zoning. Recent studies further confirm the value of using a GIS-based multicriteria analysis for the spatial identification of tourism potential (Yasin & Woldemariam, 2023; Withanage et al., 2024).

New studies also point out that suitability mapping should be based on the range of analysis and available evidence and should not include a large set of suitability criteria. Mankelkelot et al. (2026) applied land-use/land-cover, terrain, accessibility and tourism-related indicators in an integrated GIS framework, demonstrating the flexibility of the spatial suitability models and the choice of indicators based on the research objective. The evaluation in this study is intentionally limited to just two directly measurable landscape dimensions: water proximity (W) and green and natural land-cover suitability (L) and is meant to serve as a screening-level indicator for the blue-green tourism potential instead of a comprehensive tourism-development index.

Over the last few years, spatial studies have more and more focused on the link between environmental resources and regional economic vulnerability in Azerbaijan. In 2026, Qadimli et al. showed the usefulness of the geospatial information in the evaluation of the Caspian Sea as well as the country's strategic inland water resources. But, the spatial association between inland water resources, the surrounding land cover and its potentiality for blue-green tourism in the region is relatively under-researched. The Central Aran economic region is a suitable case for covering this gap, as all mentioned elements are present in one economic region: the Mingachevir Reservoir, agricultural landscapes and semi-natural land-cover elements are located in one economic region.

MATERIALS AND METHODS

Study Area

The study is carried out in the Central part of the economic region of Azerbaijan – Mingachevir city and the Agdash, Goychay, Kurdamir, Ujar, Yevlakh and Zardab districts. The area is a lowland territorial system, where urban settlement, agriculture and the major inland water resources are intermingled. The Mingachevir Reservoir and the Kura River have a strong influence on its blue spatial structure, and croplands, grasslands, wetlands and sparse vegetation with locally distributed tree and shrub cover are present on the surrounding landscape. These landscape components form a basis for the assessment of possibilities for water-based and nature-oriented recreation and integrated blue-green tourism planning. The administrative structure of Central Aran was compared with regional classification of State Statistical Committee of Azerbaijan.

Spatial processing and cartographic outputs are all carried out in QGIS. Analytical data sets were reprojected to WGS 84 / UTM Zone 38N (EPSG:32638) to ensure a consistent method of calculating distances and areas. A principal water features map and administrative divisions of the study area is shown in Figure 1.

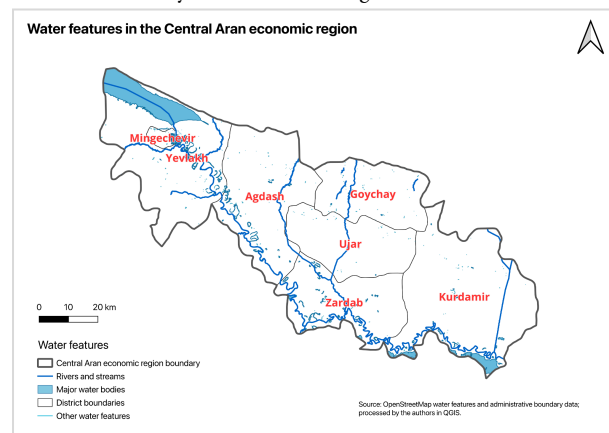


Figure 1. Water features in the Central Aran economic region of Azerbaijan.

Data sources and spatial preprocessing.

Geospatial environmental data was combined with official tourism data in the assessment. Water bodies and rivers were mapped from OpenStreetMap and cropped to the extent of Central Aran. The OpenStreetMap data is used under the Open Database License and is supplied as open and freely reusable geographic data that can be used for spatial analysis. The OpenStreetMap data is used under the Open Database License and is supplied as open and freely reusable geographic data that can be used for spatial analysis (OpenStreetMap contributors, 2026). Very small ponds and minor artificial water features were removed from the water-resource layer to minimize the impact of these water features on regional tourism suitability.

Land-cover conditions were based on a global 10 m land-cover product (ESA WorldCover 2021 v200) produced from Sentinel-1 and Sentinel-2 observations (Zanaga et al., 2022). The product delivers land-cover data at 10 m spatial resolution, with a global consistency. Two WorldCover tiles were mosaicked and clipped to the study area and reprojected using nearest neighbour resampling to ensure that the original categorical land-cover information was retained.

Official tourism and accommodation indicators were obtained from the State Statistical Committee of the Republic of Azerbaijan. Tourism in Azerbaijan statistical yearbook 2013 provides indicators for hotels and similar units and other economic indicators connected with tourism, such as regional and the administrative-unit indicators. The institutional and national tourism context was provided by complementary tourism sector information from the State Tourism Agency.

Table 1. Data sources and indicators used in the assessment

Data component	Source	Spatial	Analytical use
Administrative boundaries	Official/open administrative boundary data	District level	Study-area delineation and zonal comparison
Water bodies	OpenStreetMap	Vector polygons	Identification of major water resources and water proximity analysis
Rivers and streams	OpenStreetMap	Vector lines	River-network mapping and contextual interpretation
Land cover	ESA WorldCover 2021 v200	10 m raster	Green and natural land-cover suitability assessment
Tourism accommodation	State Statistical Committee of the Republic of Azerbaijan	Administrative-unit statistics	Assessment of accommodation capacity and tourism development
Tourism activity	State Statistical Committee of the Republic of Azerbaijan	Guests, overnight stays and related indicators	Measurement of tourism intensity
Tourism context	State Tourism Agency of the Republic of Azerbaijan	Official tourism statistics and institutional information	Interpretation of tourism development priorities

Source: Compiled by the authors based on OpenStreetMap, ESA WorldCover 2021 v200, the State Statistical Committee of the Republic of Azerbaijan and the State Tourism Agency of the Republic of Azerbaijan.

Water proximity suitability

The proximity to water was chosen as the first spatial component (W) of blue-green tourism potential. Buffer operations in QGIS were used to create the initial proximities from vector features, based on distance (QGIS Development Team, 2026). Water bodies were selected and buffers with varying distances from water sources were created. Five non-overlapping distance zones were produced using buffer, clip and difference operations in QGIS:

- $\leq 0.5 \text{ km} = 5$ (very high suitability);
- $0.5\text{--}1 \text{ km} = 4$ (high suitability);
- $1\text{--}3 \text{ km} = 3$ (moderate suitability);

- $3\text{--}5 \text{ km} = 2$ (low suitability);
- $> 5 \text{ km} = 1$ (very low suitability).

The classification is based on the assumption that the closer to large water bodies, the more opportunities for recreation, waterfront activities and water-based tourism and that distance acts as a relative measure of spatial suitability for tourism development, not necessarily a measure of actual tourism development. Buffer operations in QGIS were used to create the initial proximities from vector features, based on distance. The classes were then combined into one Water Proximity Suitability layer (Figure 2).

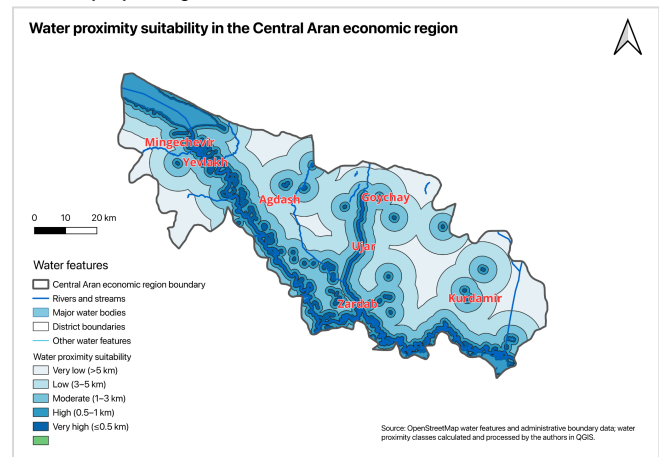


Figure 2. Water proximity suitability in the Central Aran economic region of Azerbaijan.

Suitability of green and natural land-cover

The second spatial component (L) was about recreational and ecological suitability of land cover. The ESA WorldCover classes were re-classified on a 5-point scale based on their relative contribution to nature-based recreation. Tree cover and herbaceous wetlands scored the highest (5), followed by shrubland and grassland (4), cropland (3 due to its potential relevance for rural and agro-tourism), bare or sparsely vegetated areas (2) and built-up areas (1). The permanent water bodies were not included in this component to prevent double counting as water resources were being addressed with the W indicator.

The reclassification was done in QGIS using the Raster Calculator, and resulted in the Green and Natural Land-Cover Suitability raster shown in Figure 3. By using the original 10 m WorldCover data, landscape structure could be considered at a fine-grained level without having to average things down to the district level.

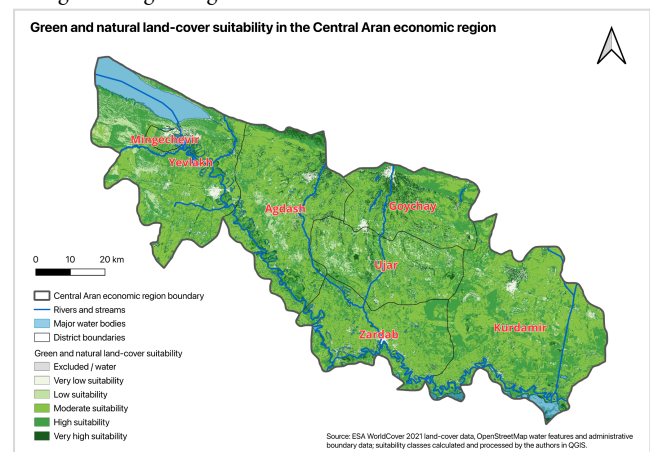


Figure 3. Green and natural land-cover suitability in the Central Aran economic region of Azerbaijan.

Tourism-development indicators integration

The spatial results were then contrasted with the official tourism-development indicators for the seven administrative units. The current intensity of the tourism activity was described with the following indicators: accommodation capacity; accommodated persons; overnight stays; and hotel related economic indicators. Indicators were standardized where necessary to make it possible to compare across administrative areas of varying population. By comparing spatial resource suitability with tourism activity, areas that seem to be relatively underused in terms of blue-green tourism resources were highlighted and territorial differentiated sustainable tourism development priorities were formulated.

RESULTS AND DISCUSSION

Water resources and water proximity suitability in spatial distribution

Spatial analysis showed that the distribution of blue resources is by far not even in the Central Aran economic region. As seen in Figure 1, the main hydrological features are the Mingachevir Reservoir and Kura River corridor, which constitute the main continuous blue feature in the study area. There are smaller surface-water features scattered throughout Agdash, Goychay, Ujar, Zardab and Kurdamir, but these are not as spatially continuous.

This territorial differentiation is reflected in a water-proximity suitability assessment (Figure 2). Within 0.5 km of selected major water bodies are very-high-suitability areas, with suitability declining with distance. High suitability and very high suitability is very concentrated around Mingachevir Reservoir and along the corridor of Kura River, including within and around Mingachevir, Yevlakh and Zardab. The areas thus have a relatively good spatial foundation for water front recreation, water-based tourism and landscape oriented visitor activities.

This is in line with the overall knowledge of the inland water systems as an economic space asset as well as an ecological resource. Recent studies on Azerbaijan's strategic water systems have also pointed to the importance of taking into account hydrological conditions as well as considering socioeconomic exposure and regional development implications (Qadimli et al., 2026). Proximity to water can, then, be seen from a tourism-planning point of view as an important enabling factor, but it does not necessarily mean that tourism infrastructure is in place.

Suitability of green and natural land-cover

The land-cover suitability assessment resulted in a more varied pattern than the water-proximity indicator (Figure 3). In Central Aran, moderate-suitability areas account for a significant portion of the land area and are mostly associated with the predominance of cropland. Agricultural landscapes were scored as intermediate, as they may offer nature-based tourism but in addition they may offer rural or agro-tourism, local food experiences and landscape-based recreation.

The high and very high suitability classes are predominantly related to tree cover, shrubland, grassland and herbaceous wetlands. These areas are spatially disjointed, but when they are near water resources these areas could add value to tourism. This aligns with the research that has identified the recreational and ecosystem-service values of green infrastructure and semi-natural landscapes (Maes et al., 2015). The spatial combination of water surfaces and wetlands is therefore even more important in the context of integrated blue-green tourism planning in conjunction with vegetated surfaces.

Results further indicate that low land-cover suitability is not necessarily linked to low overall tourism potential. Built-up areas are assigned low scores for ecological suitability in the L component, but urban centres can offer visitor services, accommodation and transport

which can offset the low natural land cover value. This favours the application of the multicriteria GIS approaches, in which the suitability of tourism is evaluated based on several factors (environmental, infrastructural and accessibility) instead of a single one (González-Ramiro et al., 2016).

Differentiation of the blue-green tourism potential by territories

The combination of the W and L indicators demonstrates different development patterns that are geographically distinct. An important element of blue-green tourism, major water resources combined with appropriate green and semi-natural landscapes and an existing urban centre are characterized by the Mingachevir and the reservoir zone. The Mingachevir-Yevlakh region could thus become a key node point for water-based recreational activities and sustainable tourism development in the region.

Another strategic spatial axis is the Kura River corridor towards Zardab. Much of this corridor is highly suitable for water proximity tourism, and the rural and nature-based tourism opportunities are provided by the surrounding agricultural, wetland and semi-natural landscapes. The sustainable development of this corridor should focus on low impact recreation, managing access to the river and environmentally sensitive visitor facilities. This is particularly relevant as the economic potential of strategic inland waters can be impacted due to the effect of environmental and hydrological change (Qadimli et al., 2026).

The profile of Agdash and Goychay is a bit different. They are more fragmented in terms of blue resources and the agricultural and green land-cover components are relatively large. These districts might therefore be better suited for tourism models involving the rural scenery to the extent that agro-tourism and local recreational resources are involved. Larger areas with relatively low water-proximity suitability, such as Ujar and Kurdamir, show that strategies aimed at tourism alone would be less suitable and alternative rural activities, based on the culture and accessibility of the area, should be taken into consideration.

Sustainable development implications

The spatial results suggest that Central Aran is not a single tourism destination, but rather a variety of destinations. Territorially differentiated development strategies are required as a function of the various combinations of water availability, natural land cover, agricultural landscapes and settlement structure. In this context GIS based suitability assessment can be useful as allows the systematic comparison of tourism resources and spatial constraints and can be used for more targeted regional planning (González-Ramiro et al., 2016).

Additionally, there are also needs for adequate financing mechanisms to implement the blue-green tourism priorities. Green investment products may be needed for environmentally friendly visitor facilities, landscape restoration, water-sparing infrastructure and small tourism businesses. A previous research conducted in Azerbaijan has shown the role of green finance instruments in the support of environmentally sustainable investment and the overall green transition (Sadiqov et al., 2026). Meanwhile, public awareness and involvement in environmentally oriented development are also essential elements, especially if long-term sustainability requires behavioral and societal involvement (Mammadov, 2025).

In general, the most intense spatial opportunities are related to the Mingachevir Reservoir and the Kura River system, the rest of the districts showing more and less distributed clusters of blue and green assets. The results presented here add to a differentiated approach towards the various regions, where water-oriented tourism is the focus

in the blue corridors with the best water proximity, but more intensively in rural, agro-tourism or landscape-based approaches in areas with weaker water proximity but suitable land-cover features.

CONCLUSIONS

The purpose of this research is to assess the suitability of blue-green tourism in the Central Aran economic region of Azerbaijan from spatial aspect on the basis of two indicators: water proximity suitability and green and natural land-cover suitability with the help of GIS. The results show that this blue-green tourism resource is not evenly distributed throughout the region, but has a spatially uneven distribution. The best prospects for water are located around the Mingachevir Reservoir and on the corridor of the Kura River, especially around Mingachevir and Yevlakh, and on the way to Zardab. The land-cover analysis, however, shows a more complex picture where agricultural landscapes cover large areas, and areas of tree cover, grassland, shrubland and wetlands create localized areas of higher natural suitability.

The results corroborate the general findings from the tourism literature that underpinned by GIS, spatial variation in environmental resources can be an appropriate basis to differentiate development priorities (Nino et al., 2017; Yasin & Woldemariam, 2023; Withanage et al., 2024). Concurrently, the results should be viewed as a first preliminary spatial suitability assessment and not as an overall tourism potential index. The model does not directly measure road accessibilities, accommodation capacities, tourism demand, visitor preferences or investment feasibility. The dimensions should be considered in further studies and can be integrated into a more extensive multicriteria decision support model, as in more extensive GIS-based ecotourism assessments (Zabihi et al., 2020; Mankelkelot et al., 2026).

Despite this, the current study reveals a spatial foundation of the territorial differentiation of sustainable tourism planning. However, the Mingachevir Reservoir and the Kura River corridor may be more suitable for environmentally sensitive water-oriented recreation and the districts with less blue-resource proximity may benefit more from rural, agro-tourism and landscape-based development strategies. Field validation of W and L indicators should be included in future research together with information on tourism infrastructure, accessibility and socioeconomic indicators prior to investment-level decision making.

AUTHOR CONTRIBUTIONS

Conceptualization, N.Q. and U.M.; methodology, U.M.; formal analysis, U.M.; data curation, U.M.; visualization, U.M.; validation, N.Q.; writing—original draft, U.M.; writing—review and editing, N.Q. and U.M.; supervision, N.Q. All authors have read and agreed to the final version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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DATA AVAILABILITY

The spatial data used in this study were obtained from publicly available sources, including OpenStreetMap and ESA WorldCover 2021. The processed datasets and derived spatial outputs generated during the study are available from the corresponding author upon reasonable request.

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From environmental hotspots to strategic action: a life cycle assessment of solid tyre manufacturing in Sri Lanka under EU sustainability pressures

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Keywords

Environmental Hotspots, European Union, Life Cycle Assessment, Solid Tyres, Sustainability Pressures

ABSTRACT

This study evaluates the cradle-to-gate environmental performance of solid tyre production in Sri Lanka, focusing on raw material extraction and manufacturing stages. A Life Cycle Assessment (LCA) was conducted in accordance with ISO 14040 and 14044 standards using the SimaPro Faculty version. The ReCiPe 2016 Midpoint (H) method was employed to quantify 18 environmental impact categories. Primary data were collected from a leading Sri Lankan solid tyre manufacturing facility and supplemented with secondary data from Ecoinvent V3.11. This study is the first to assess the environmental impacts of solid tyre production in Sri Lanka. The total global warming potential was 160.94 kg CO₂-eq per solid tyre produced. The study finds that key raw materials such as carbon black, SBR, crumb rubber, and chemical additives, along with energy-intensive processes, drive most impacts. The findings suggest replacing high-impact materials with cleaner or bio-based ones and shifting to renewable energy like solar can greatly reduce environmental impacts. These changes are environmentally and strategically beneficial, helping Sri Lanka maintain access to markets like the EU and strengthening its position as a sustainable tyre producer.

INTRODUCTION

Tyres are one of the most significant products of the global rubber industry. As demand continues to rise sharply, several factors have reshaped competition within the industry, with sustainability among the most important. For instance, the European Union has implemented stringent environmental and chemical regulations on its exports, increasing sustainability compliance for products consumed in those countries. Major EU regulations include the Deforestation Regulation (EUDR), Chemical Regulation (REACH), EU tyre labelling (Regulation (EU) 2020/740), EU Microplastics Regulation, Extended Producer Responsibility (EPR) (UN Environment, 2024), and the Ecodesign for Sustainable Products Regulation (ESPR) (European Commission, 2025a; European Commission, 2025b). These evolving regulatory requirements and policy instruments make it mandatory for manufacturers to embed sustainability in strategic decision-making and long-term competitiveness.

Sri Lanka has been ranked as the world's largest solid tyre manufacturer in 2023, meeting nearly 28% of global demand, which accounts for 3.61% of Sri Lanka's total exports. According to the records, the European Union is one of the major destinations for Sri Lankan solid tyres (Sri Lanka Export Development Board (SLEDB), 2025; Sri Lanka Rubber Industry Master Plan – 2017 – 2026 | EDB Blog, 2017). According to the International Trade Centre's Trade Map, in 2024, solid and cushion tyres accounted for the largest share

of Sri Lanka's rubber exports to the EU27, at 49.4%. To sustain this competitive position, the industry must align with international environmental performance standards. Despite this importance, comprehensive life-cycle data for Sri Lankan solid tyre production remain unavailable, hindering informed decision-making to support cleaner production and global regulatory compliance.

Although global interest in tyre-related research is strong, with a concentration in the US, China, and Europe, Asia receives less attention (Wang et al., 2023). Moreover, several data gaps on tyre pollution have been identified in developing countries, limiting understanding of global complexities and hindering risk management within the industry (Mayer et al., 2024). Globally, tyre-related studies have predominantly focused on the use and disposal phases (Torretta et al., 2015; Harrison-Obi, 2019; Sharma et al., 2000; Daniela et al., 2013; Shanbag & Manjare, 2020). No research has examined the environmental impact of raw material extraction on the manufacturing phase of solid tyres. Nevertheless, there is considerable potential to reduce the environmental impact by closely analyzing the other life cycle stages of solid tyres. Rethinking how products are offered has become a market trend, driven by the advent of sustainability and green concepts. Nowadays, businesses are reengineering their products to make them more environmentally friendly.

Given these gaps, there is a pressing need to establish baseline life-cycle data for Sri Lankan solid tyre production and to plan strategic actions

to address stringent EU regulatory pressures by identifying and addressing critical environmental hotspots. Accordingly, this study aims to evaluate the cradle-to-gate environmental performance of solid tyres manufactured in Sri Lanka by quantifying material and energy flows, and to analyze the strategic and managerial implications required under EU sustainability pressures.

LITERATURE REVIEW

According to the literature review, although numerous research studies have been conducted in the tyre industry, several data gaps remain. Defining the complete quantitative chemical compositions of tyre rubbers, variations of tyre particles across commonly used brands, and tyre types are critical research needs (Mayera, et al., 2024). Furthermore, Mayera et al. identified data gaps in fate and transport, biological and ecological effects, management and remediation, recycling, reuse, and disposal, as well as data management and toxicity assessment in tyres. Additionally, no research was found during the literature review that focused explicitly on the environmental impact of the life cycle of solid tyres. Despite the growing global interest in tyre-related research—particularly concentrated in the US, China, and Europe—Asia has received comparatively less attention (Yunxia Wang, 2023). Most existing studies focus on the use and disposal phases of tyres (Torretta et al., 2015; Harrison-Obi, 2019; Sharma, Fortuna, Mincarini, Berillo, & Cornacchia, 2000) or on the life cycle of pneumatic tyres (Daniela, Recca, & Cicala, 2013; Shanbag & Manjare, 2020). However, research examining the environmental impact of raw material extraction through to the manufacturing stage of solid tyres and the risk to the sustainability of Sri Lankan solid tyres under EU pressures is virtually absent. Addressing this gap presents an opportunity to mitigate environmental impacts by closely analyzing these overlooked life cycle stages. As sustainability and green business concepts grow, companies are increasingly reengineering products to deliver environmentally friendly alternatives, making this research timely and relevant. Therefore, this research aims to identify and quantify the cradle-to-gate life cycle impact of tyres, especially solid tyres, in the Sri Lankan context, given their high global demand.

MATERIALS AND METHODS

This study focuses on experimental assessment of the cradle-to-gate environmental impact of solid tyres and on analysing environmental hotspots in relation to EU environmental regulations. To achieve this purpose, we employed a quantitative approach. Environmental Life Cycle Assessment was the primary tool used to quantify the environmental impact of a solid tyre. All conclusions are based on analysis of quantified primary and secondary data. The study complies with ISO 14040:2006 and ISO 14044:2006 (ISO, 2023) and uses recognized LCA tools, specifically the SimaPro Faculty version. Additionally, this software supports developing product-system models based on logic and transparency (Goedkoop et al., 2016). To quantify the impact, this study uses the ReCiPe characterization method. Because the assessment is conducted in the Sri Lankan context, the ReCiPe method is the most suitable option, as no region-specific characterization models are available. Moreover, it is the only method that covers the most midpoint impact categories. The qualification follows the following systematic approach.

The goal of the study is to calculate the adverse environmental impact of an average solid tyre from raw material extraction to manufacturing. Figure 1 shows the average solid tyre considered.



Figure 1 An average resilient solid tyre

The study was conducted within the cradle-to-gate boundary level. The declared unit is one industrial solid tyre weighing 46.5 kg, with a sectional width of 7.00 inches and a rim diameter of 12 inches. The study is conducted within the boundary, from the extraction of primary raw materials to the factory gate of the solid tyre. Figure 2 below presents a detailed system boundary of an average industrial solid tyre.

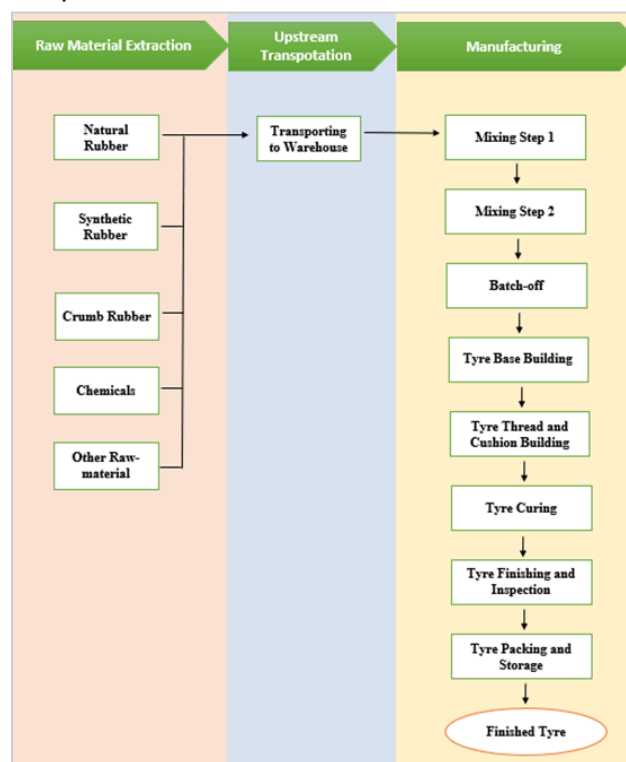


Figure 2. Detailed system boundary of an average industrial solid tyre (Developed based on the information gathered during the study-2026)

According to Figure 2, the natural rubber extraction includes the SLR-20 (Standard Lanka Rubber) rubber type. The synthetic rubber manufacturing stage includes SBR (Styrene-butadiene rubber). The crumb rubber is a type of recycled rubber. Chemicals include all the antioxidants, stabilizers, plasticizers, etc., used in solid tyre manufacturing. Other raw materials used in solid tyre manufacturing include steel, carbon black, and textile materials.

After raw materials from several locations are transported to the manufacturing plant, production begins. The manufacturing phase encompasses mixing, batch-off, tyre base building, tyre tread and cushion building, curing, finishing, inspection, and packing and storage. In each phase and process, emissions to water, soil, and air should be examined. Figure 3 represents the summarized system

boundary of the study. Tyre inspection, packaging, and storage are excluded from the analysis.

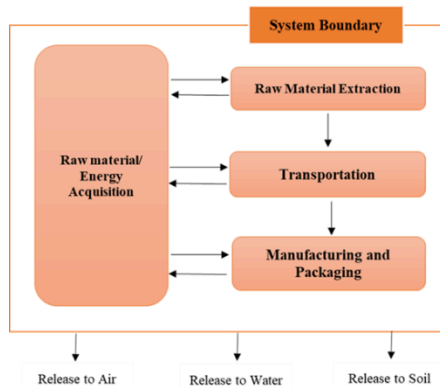


Figure 3. Summarized System boundary of the LCA study of the referenced solid tyre (Developed based on the information gathered during the study-2026)

After precisely defining the goal and scope of the study, the required data should be gathered to achieve the defined goal successfully within the demarcated boundary. All input data, including raw materials, energy, and other resources used, and output data, including products, co-products, and emissions to air, water, and soil, in quantities (activity data), should be collected for each unit process, as shown in Figure 4, using primary or secondary sources.

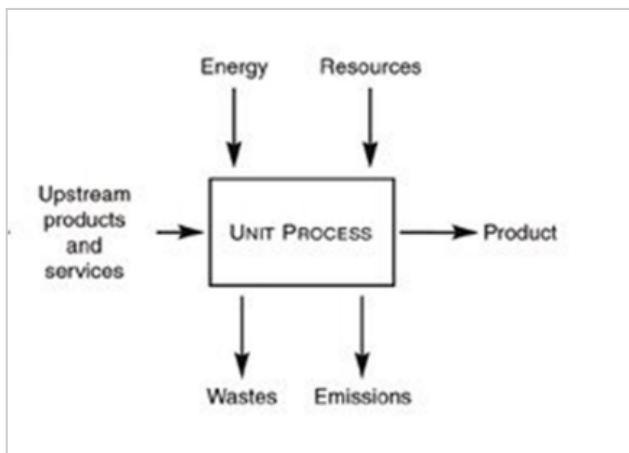


Figure 4. Life cycle inventory of unit process

Source: (Kuczenski, Geyer, & Boughton, 2010)

For instance, in SLR-20, the natural rubber manufacturing process, the amount of natural latex used, water consumption, electricity, diesel, packaging used, etc., are identified as inputs and wastewater generated and greenhouse gas emissions are identified as wastes.

Both primary and secondary data were used to develop the life cycle inventory. Secondary data were sourced from the Ecoinvent database (version 3.11, cut-off) to model upstream processes, including the production of synthetic rubber, carbon black, and chemical additives.

Next, the collected data were analyzed using sophisticated software (SimaPro – Faculty Version). Among many other LCA tools, such as GaBi and OpenLCA, SimaPro is preferred for academic- and professional-level Life Cycle Assessments. It allows modelling and systematic analysis of complex life cycles (Hillege, 2025). SimaPro is one of the most widely used software applications for Life Cycle Assessment, particularly in academic and consulting domains, due to its comprehensive modelling capabilities and integration with databases such as Ecoinvent (Hauschild et al., 2018). Moreover, SimaPro is more flexible and easier to edit and access LCI databases (Chen et al., 2024). ReCiPe 2016 Midpoint (H) and ReCiPe 2016

Endpoint (H) methods were used to evaluate environmental impacts and damage categories, respectively. These methods were chosen because they can pinpoint particular environmental hotspots, enabling more focused management actions.

The results are presented as characterized figures, normalized figures, tables, and networks. In this phase, the potential environmental impacts embedded in the inputs and outputs identified in the previous stage are evaluated. The environmental impacts are characterized by 18 impact categories, including climate change, resource depletion, human carcinogenic toxicity, and water pollution. To assess the broader implications of these impacts, endpoint damage categories were used, covering damage to human health, ecosystems, and resources. This analytical approach enhances understandability for both technical and managerial audiences.

Finally, the resulting data are interpreted and analyzed to derive meaningful conclusions about the product, process, or system. At this phase, the extent to which the impact can be reduced or avoided can be compared across alternatives to inform recommendations and improvements.

In addition, a separate scenario analysis assessed potential pathways for reducing environmental impact. Under this analysis, researchers compared a transition from conventional energy (grid electricity) to renewable energy (solar power) in the manufacturing stage of solid tyre production, holding other parameters constant. This comparison provides information on potential reductions in environmental impact for relevant sustainability expectations of export markets, as well as practical insights for managerial and strategic decision-making.

RESULTS AND DISCUSSION

Cradle-to-gate life cycle inventory and process overview of an average solid tyre

One foundational requirement for understanding the strategic actions needed to meet strict global customer requirements is quantifying the environmental impact of an average solid tyre manufactured in Sri Lanka. In this pursuit, understanding the production flow and developing the life-cycle inventory are critical. Figure 5 below illustrates the process for manufacturing resilient solid tyres in Sri Lanka.

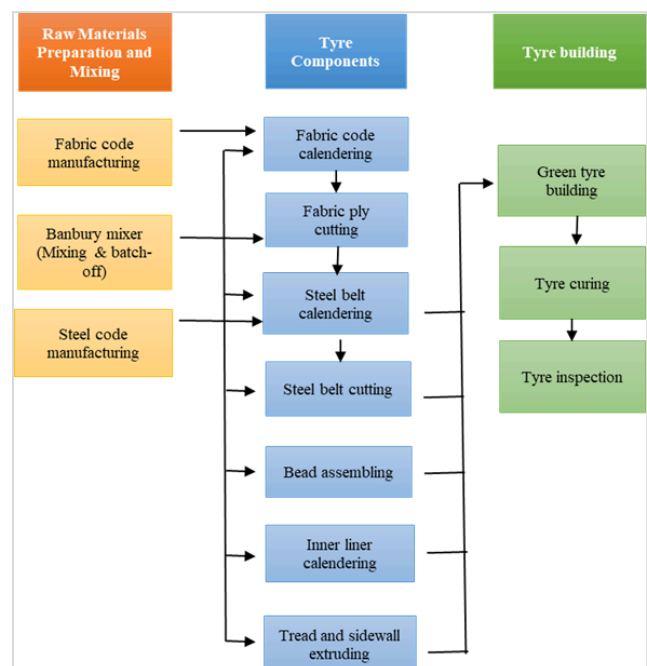


Figure 5. Manufacturing process of resilient solid tyres

As shown in Figure 5, manufacturing solid tyres is a complex, time-consuming process. Generally, solid tyres are built around a metal frame that can be mounted to a specific vehicle (Apexway, 2022). The raw materials needed to build the basic structure of a solid tyre are steel rings and rubberized fabric sheets. The beads are coils of monofilament steel wires (Nideost & Walters, 2000). Overall, the manufacturing process can be summarized in four main stages: Mixing, Batch-off, Tyre Building, and Tyre Curing. The analysis excludes the tyre inspection, packaging, and storage stages.

At the mixing stage, the required materials and chemicals are combined in specific proportions to prepare the compounds needed for the different sheets/layers of the tyre. Compounding is done to enhance the tyre's solid properties. The factory manufactures steel rings separately. The rubberized fabric sheets/layers are cooled in the batch-off stage. A green tyre, which is a semi-finished solid tyre, is built using steel rings and cooled rubberized fabric sheets/layers. This consists of three layers: the base layer, the cushion layer, and the tread layer. Then the green tyre is put into a mould and heated, allowing the rubber to vulcanize. This process is known as tyre curing. The cured, or finished, tyre can then be sent for tyre inspection. Each sub-process adds value to the final output. Based on these summarized production processes, the life cycle inventory is developed as shown in Table 1 below.

Table 1. Inputs and outputs of the solid tyre manufacturing phase

Process	Input Name	Unit	Quantity	Output Name	Unit	Quantity
Mixing	Natural Rubber	kg	15.777	Compound Waste	kg	1.648
	SBR	kg	6.852	Waste Water	l	5.645
	Crumb Rubber	kg	5.101			
	FRC (10mm)	kg	2.480			
	Cotton Flock	kg	0.571			
	Carbon Black	kg	13.860			
	VN3	kg	0.571			
	Zinc Oxide	kg	0.862			
	Stearic Acid	kg	0.498			
	ZDEC	kg	0.030			
	TETD	kg	0.014			
	CBS	kg	0.303			
	Struktol A 95	kg	0.950			
	Si69	kg	0.288			
	TMQ	kg	0.138			
	6PPD	kg	0.344			
	Wingstay 100	kg	0.047			
	PVI	kg	0.025			
	Sulfur	kg	0.510			
	C5 Resin	kg	0.229			
	40MS	kg	0.154			

	MJP	kg	0.549			
	Steel	kg	0.486			
	Water (Cooling)	l	5.645			
	Electricity	kWh	26.315			
Batch-off	Soap	kg	0.011	Waste Water	l	5.113
	Water (Dipping)	kg	2.345			
	Water (Cooling)	l	2.768			
	Electricity	kWh	15.760			
Tyre Building	Electricity	kWh	0.441	Compound Waste	kg	2.01
Tyre Curing	Electricity	kWh	1.476	Flash	kg	0.45
	Steam	kg	45.481			

Table 1 presents all inputs and outputs for manufacturing a resilient solid tyre. Mass balance closes to within 0.1%: total material input is 50.65 kg (50.64 kg of compounding materials plus 0.01 kg of soap), against 4.11 kg of solid process losses (3.66 kg compound waste and 0.45 kg curing flash), giving a finished tyre mass of 46.54 kg (declared as 46.5 kg). Water is assumed to leave each stage entirely as effluent, with 10.76 L input and 10.76 L wastewater across mixing and batch-off; evaporative losses and cooling-water recirculation are not modelled, which is a conservative assumption for plant water consumption. The primary raw materials used in manufacturing solid tyres are natural rubber (SLR-20, Standard Lanka Rubber), SBR (Styrene-butadiene rubber), a synthetic rubber, crumb rubber, a recycled form of rubber, and carbon black. Natural rubber and crumb rubber are sourced from Sri Lanka, and SBR is sourced from Poland. FRC (Fibre-reinforced rubber compound) is a type of upcycled rubber. Carbon black, Cotton flock, and VN3 (precipitated silica) are used as fillers in the manufacturing of solid tyres. Zinc oxide, Stearic acid, ZDEC (Zinc Diethyl Dithiocarbamate), CBS (Cyclohexyl Benzothiazole Sulfenamide), and TETD (Tetraethylthiuram disulfide) are accelerators used in the compounding process. Struktol A 95 and Si69 (Silane) are coupling agents, and TMQ (2,2,4-trimethyl-1,2-dihydroquinoline), 6PPD (N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine), and Wingstay 100 are antioxidants. Pre-Vulcanization Inhibitor (PVI) is a retarder, and Sulfur is a curing agent. As Hydrocarbon resins, C5 resin, and 40MS are used. MJP is a plasticizer used in rubber compounding. Additionally, steel is used to manufacture rings that form part of the base layer. Steel is imported from China. All other raw materials are imported from India. Water is used mainly for washing and cooling purposes.

Grid electricity powers the process. Steam energy is used for tyre curing. The process outflows are identified as compound waste and water waste in the mixing, batch-off, and tyre-building processes. It is assumed that the total amount of water used as input leaves the process as wastewater, with no losses. Furthermore, it is assumed that there are no electricity losses during the process. Flash is the excess amount of tyre particles that are melted during the tyre curing process. The total weight of all materials used to manufacture the solid tyre is 50.6 kg. After deducting all the waste, the net weight of the solid tyre is 46.5 kg. This life cycle inventory lays the basis for the environmental impact assessment presented in the following section.

Overall environmental impact profile

Table 2 below presents the characterized environmental impact of a solid tyre from raw material extraction to manufacturing.

Table 2. Total Characterized Cradle-to-Gate Environmental Impact of a Solid Tyre

Impact category	Unit	Total
Terrestrial ecotoxicity	kg 1,4-DCB	466.4289
Global warming	kg CO ₂ eq	160.9458
Human non-carcinogenic toxicity	kg 1,4-DCB	115.6244
Fossil resource scarcity	kg oil eq	61.1829
Water consumption	m ³	30.8527
Land use	m ² a crop eq	11.5502
Human carcinogenic toxicity	kg 1,4-DCB	5.3858
Marine ecotoxicity	kg 1,4-DCB	4.8284
Freshwater ecotoxicity	kg 1,4-DCB	3.5960
Ionizing radiation	kBq Co-60 eq	2.1654
Terrestrial acidification	kg SO ₂ eq	0.9629
Ozone formation, Terrestrial ecosystems	kg NO _x eq	0.6419
Ozone formation, Human health	kg NO _x eq	0.6127
Mineral resource scarcity	kg Cu eq	0.5510
Fine particulate matter formation	kg PM _{2.5} eq	0.3568
Marine eutrophication	kg N eq	0.0484
Freshwater eutrophication	kg P eq	0.0409
Stratospheric ozone depletion	kg CFC11 eq	0.0001

According to Table 2, the global warming impact of the solid tyre under study is 160.9458 CO₂ eq. Water consumption is recorded as 30.8527 m³ per solid tyre under study. The human carcinogenic impact is equivalent to 5.3858 kg of 1,4-DCB per one solid tyre. According to the normalized impact categories, which are comparable (unitless), respectively, human carcinogenic toxicity (0.5230), freshwater ecotoxicity (0.1428), water consumption (0.1157), marine ecotoxicity (0.1111), freshwater eutrophication (0.0630), fossil resource scarcity (0.0624), ozone formation - terrestrial ecosystems (0.03614), terrestrial ecotoxicity (0.03069), ozone formation - human health (0.0298), terrestrial acidification (0.0235), and global warming (0.0201) showed the highest significance. The results indicate that environmental impacts are significant and multidimensional, with both climate- and human-health-related implications.

This result is corroborated by the damage assessment results for the cradle-to-gate life cycle of a solid tyre. According to the normalized results, the most serious damage from cradle-to-gate solid tyres is to human health (0.019895046). Apart from the high human carcinogenic toxicity recorded, all other identified impact categories have a direct or indirect adverse impact on human health. The resulting characterized damage to human health is 0.000477 Disability Adjusted Life Years (DALYs). This means the cradle-to-gate impact of one solid tyre under study can cause 0.000477 years of ill-health,

disability, or early death for human beings. However, this figure is a globally averaged indicator of potential damage based on marginal characterisation models. It does not depict observed or attributable health outcomes in any particular population and should be used primarily for comparing design options, not as an absolute measure of harm.

Understanding the difference between normalised midpoint significance and endpoint damage is essential for interpretation. When measured on a normalised midpoint basis, human carcinogenic toxicity appears highest, mainly due to the low normalisation reference for that category rather than a large absolute burden. In contrast, at the endpoint level, the total human-health damage of 4.77×10^{-4} DALY per declared unit is mainly due to fine particulate matter formation and global warming, which together make up about three-quarters of the total. Carcinogenic toxicity accounts for less than 5%. Both pathways primarily originate from coal-based grid electricity, highlighting energy substitution as the most effective intervention. Although toxicity-related categories are smaller in endpoint terms, they remain strategically important because EU chemicals regulation directly targets them.

Higher production levels lead to higher DALYs. If the average annual solid tyre production in Sri Lanka is assumed to be 100,000 units, the total damage to human health is 47.7 DALYs. This reflects the materials, energy, and processes used from raw material extraction to the manufacturing stage of one solid tyre.

Environmental impact distribution across life cycle stages

To identify the life-cycle stage-wise distribution of environmental impacts, the total result was categorized into three stages, as defined in the European standard EN 15804: A1, A2, and A3, representing the Cradle-to-Gate scope. A1 covers raw material extraction, A2 covers transport to the factory, and A3 covers the manufacturing stage. According to the SimaPro results, the normalized impacts were distributed among the defined life cycle stages. Figure 6 below depicts the graphical representation of the results. Normalized impact categories are used for comparison purposes here.

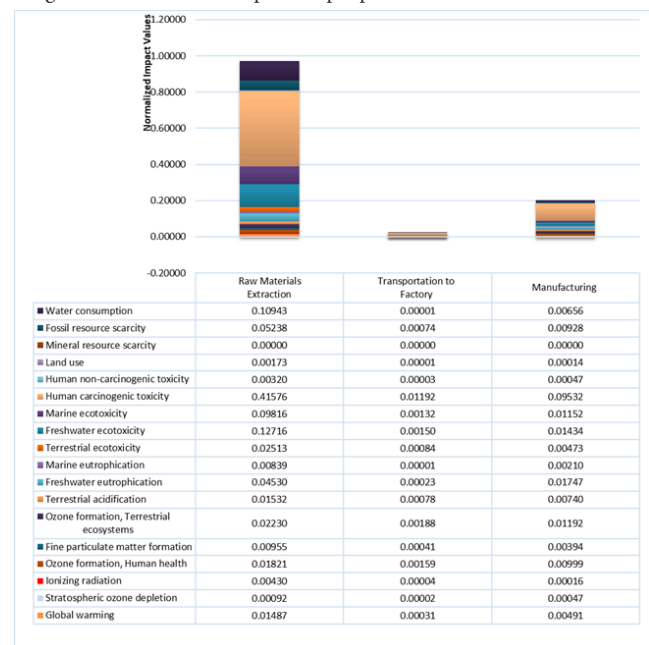


Figure 6. Cradle-to-Gate environmental Impact of a Solid Tyre (Derived by running the SimaPro Faculty version under the ReCiPe characterization method - 2026)

As shown in Figure 6, the highest environmental burden of a solid tyre within the scope of cradle-to-gate is recorded in the raw material extraction phase. Among the environmental impacts generated during raw material extraction, human carcinogenic toxicity contributes the most. The raw materials used for the manufacturing of a solid tyre generate a considerable proportion of harm to human beings in terms of cancer, as supported by the previous analysis. The second- and third-highest environmental impacts in the raw material extraction phase are freshwater ecotoxicity and water consumption, respectively. Global warming also shows a normalized impact of 0.01487.

Among the identified primary life-cycle stages of a solid tyre, the manufacturing stage is the second most significant contributor to the environmental burden. As with the raw material extraction phase, human carcinogenic toxicity contributes most. Here, during the manufacturing phase, the primary activities considered are energy and water consumption for producing a solid tyre. The two energy sources considered are electricity and steam. Freshwater ecotoxicity, freshwater eutrophication, and marine ecotoxicity are other significant environmental impacts from manufacturing a single solid tyre.

According to Figure 6, upstream transportation is less significant than the other two stages. Based on the data collected, most raw materials, except SLR-20, crumb rubber, SBR, and steel, are imported from India. SLR-20 and crumb rubber are locally sourced, and therefore, only land transportation was considered. SBR and steel are imported from Poland and China, respectively. For all foreign-sourced raw materials, sea transportation is also considered, in addition to land transportation from the supplier's location to their harbour and local land transportation (from Colombo harbour to the manufacturing plant). However, in upstream transportation, as in the other two life cycle stages, the highest-impact category recorded is human carcinogenic toxicity. In conclusion, the results indicate that upstream material choices play a more critical role than downstream processing in determining environmental performance.

Identification of environmental hotspots

The results above show that identifying material-based hotspots is essential for managerial decisions to avoid or mitigate environmental impact and meet global regulatory pressures. Figure 7 below compares inputs by their environmental impact contribution. Normalized impacts are used for comparison.

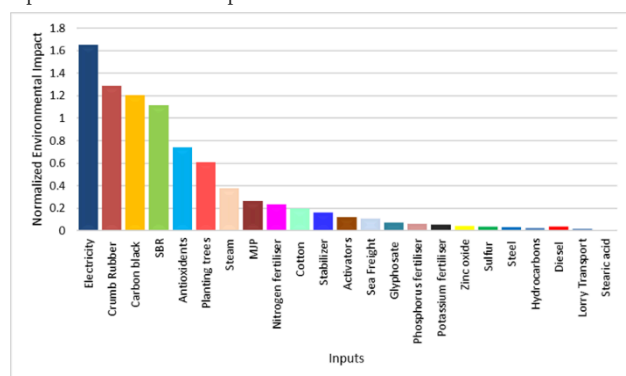


Figure 7. Comparison of Environmental Impact Contribution of Inputs used in Solid Tyre Manufacturing (Derived by running the SimaPro Faculty version under the ReCiPe characterization method - 2026)

According to the results in Figure 7, the major contributors to environmental or human health damage are electricity, crumb rubber, carbon black, SBR, and chemicals in total, as well as tree planting. The highest-impact category identified above is human carcinogenic toxicity. Grid electricity consumption is the primary contributor to this impact, a conclusion corroborated by existing literature. For

instance, coal-powered electricity generation has several detrimental impacts on human health. Persistent inhalation of pollutants generated by coal combustion can damage the lungs, immune system, heart, DNA, brain, and reproductive system in humans (Gasparotto & Da Boit Martinello, 2020; Chen et al., 2017; Weldu et al., 2017). Electricity is highly consumed throughout the solid tyre manufacturing process, including compound preparation (mixing), batch off, tyre building, and tyre curing. According to life-cycle inventory analysis, the solid tyre manufacturing process consumes 43.992 kWh of electricity. In Sri Lanka, electricity is mainly generated by burning coal.

Several studies have shown that coal-based electricity generation results in the emission of numerous toxic pollutants, including mercury, lead, sulfur dioxide, nitrogen oxides, particulates, and heavy metals, which can have a significant adverse impact on the quality of the environment and human health (Weldu, Assefa, & Jolliet, 2017). Burning coal emits toxic pollutants, including sulfur dioxide, Nitrogen Oxides, Carbon dioxide, Fly ash, and toxic metals. These pollutants can contaminate groundwater and also cause land pollution (EPA, 2025). According to the United States Environmental Protection Agency, reductions in plant biodiversity, acid rain, and changes in biological communities are among the other adverse effects of coal-fired electricity generation. These factors may contribute to the significant environmental burden associated with electricity consumption in solid tyre manufacturing in Sri Lanka.

Second, Figure 7 shows that crumb rubber is the next-highest contributor to the negative environmental impact of the cradle-to-gate solid tyre life cycle. To produce a 46.5 kg solid tyre, 5.101 kg of crumb rubber should be incorporated. Crumb rubber is a type of recycled rubber derived from used tyres. According to the results obtained, the normalized impact of crumb rubber is 1.284. Although it is considered an environmentally friendly raw material, researchers have found that crumb rubber could threaten aquatic and soil organisms (Fort et al., 2022). Studies have found that the crumb rubber manufacturing process contaminates water with BOD₅, COD, TSS, ammonia, and total nitrogen. The drying process can also cause air pollution, including SO₂, NO₂, HCl, NH₃, and other harmful emissions (Yerdianti & Aziz, 2021).

The third most significant contributor to the negative environmental impact of the cradle-to-gate solid tyre life cycle is carbon black. According to the LCIA results, 13.860 kg of carbon black is consumed in producing one solid tyre under study. The normalized environmental impact of carbon black used is 1.199. According to Coppola et al., carbon black is a carbonaceous residue with unique chemical and optical characteristics, primarily produced by the incomplete combustion of organic materials such as biomass and fossil fuels. Studies have shown that carbon black harms air quality, agriculture, forests, human health, the economy, and the environment (Tiwari, Chen, Singh, Singh, & Srivastava, 2021). Carbon black in the atmosphere, soil, glaciers, water bodies, and human bodies has detrimental effects on global carbon cycling, climate change, and human health (Coppola et al., 2022). These factors help explain the significance of carbon black's adverse environmental impact, as illustrated in Figure 7.

Additionally, SBR has a significant adverse environmental impact, as shown in Figure 7. SBR has been identified as a major source of microplastics, which have a high potential to harm the environment, including land, water, and air (Järlskog, 2020; Zhao et al., 2021). According to the LCIA, a 46.5 kg solid tyre contains 6.852 kg of SBR, most of which is in the tread layer, the tyre's outermost layer.

According to Figure 7, antioxidants are the next highest contributor to negative environmental impact. Antioxidants used in solid tyre manufacturing, including 6PPD and TMQ, are also identified as major contributors to the selected solid tyre's negative environmental impacts. The results indicate that the normalized environmental burden of antioxidants used is 0.738. Regarding 6PPD, researchers have found that 6PPD and 6PPD-Quinone, present in tyre wear dust, cause adverse environmental impacts, especially to aquatic life. Researchers have uncovered that there is a relationship between Coho salmon deaths and 6PPD. As a result, tribes in Washington requested a ban on 6PPD in 2023 (Shanbag & Manjare, 2020). In addition to that, 6PPD and 6PPD quinone have been detected in the bloodstreams of children and adults, including pregnant women in China, probably entering through the inhalation of tyre particles (Bohara et al., 2025). This evidence supports the significant human carcinogenic impact of the cradle-to-gate life cycle of the solid tyre under study. Therefore, Sri Lankan tyre manufacturers should seriously consider using antioxidants such as 6PPD in solid tyre production.

In addition to these five primary contributing inputs, planting trees, nitrogen fertilizer, glyphosate, phosphorus fertilizer, and potassium fertilizer are also used in TSR production (SLR-20 in this study). The normalized impacts are 0.609, 0.234, 0.072, 0.059, and 0.051, respectively. Several socioeconomic and environmental impacts have been identified in the rubber tree planting process, including damage to soil quality and groundwater reserves, biodiversity loss, deforestation, and microclimatic changes (Ochigbo, Lafia-Araga, & Suleiman, 2011; Panda & Sarkar, 2020). Glyphosate, a commonly used herbicide, is also relevant in this regard. The International Agency for Research on Cancer (IARC) has classified glyphosate as carcinogenic (Tarazona et al., 2017).

In terms of water consumption, SimaPro process contribution results indicate that the highest water consumption in cradle-to-gate solid tyre production is attributed to SBR production. Studies show that “about 710 million gallons of makeup water is withdrawn daily by the styrene, butadiene, styrene-butadiene rubber (SBR), and speciality-rubber industries; 88 percent of this water is used only for once-through cooling” (Durfor, 1963). Furthermore, the cotton flock used in the base layer is highly water-intensive (Demeke et al., 2024). Moreover, in crumb rubber production, if the wet process is used, the crumb rubber is mixed with asphalt at the plant before being combined with aggregate. This method may require water for mixing and cleaning (Public Works Construction, 2015). In addition, freshwater and marine ecotoxicity can occur when fertilizers and chemicals are added to waterways, as discussed above.

In conclusion, the concentration of impacts in a limited number of inputs suggests that material selection is a primary driver of environmental performance. Moreover, comparing the environmental impact contributions of individual inputs used in solid tyre manufacturing provides essential information on areas that should be the focus of further research and development by solid tyre manufacturers.

Scenario analysis: grid electricity & solar energy

The analysis above identified grid electricity use as the major driver of most environmental impacts. Ultimately, these impacts significantly harm human health. Therefore, it is important to consider replacing grid electricity with a renewable energy option to reduce the identified impacts. Figure 8 below compares the major impact variations between using solar power and grid electricity as the main energy source in the manufacturing stage of a solid tyre. When generating the

results, it is assumed that 100% coal-powered electricity is replaced with 100% solar energy, with no emissions or impacts in the installation stage.

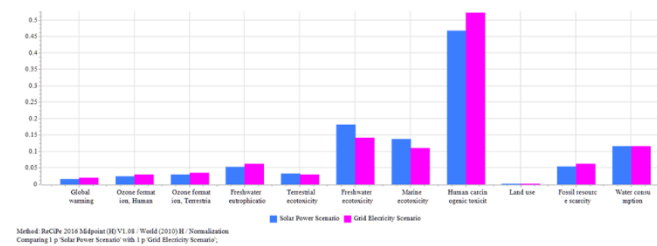


Figure 8. Comparison between using grid electricity and solar power in the manufacturing of a solid tyre

According to Figure 8, replacing grid electricity with solar energy has both positive and negative impacts, with the positive impacts more prominent. Most significantly, replacing the main energy source with solar power has decreased global warming impact by 20%, ozone formation (human health) by 18%, freshwater eutrophication by 15%, human carcinogenic toxicity by 10%, and land use by 4%. The results show that the energy transition alone can significantly reduce the carbon footprint, human carcinogenic toxicity, and numerous other impact categories, underscoring its importance as a strategic intervention.

Managerial implications for facing strategic risks under EU Sustainability Pressure

Sri Lanka, the world's leading solid tyre manufacturer, which caters to a significant share of global demand and has the EU as one of its major customers, faces multiple risks if manufacturers do not opt to switch to more environmentally and human-friendly production methods. According to the analysis, high global warming potential can increase the risk of carbon-related trade measures and buyer rejections in the future. This can directly threaten Sri Lankan solid tyre export competitiveness. High carcinogenic toxicity can expose a product to regulatory compliance risks, such as REACH, and consequently to future product restrictions. According to industry sources, EU buyers are also demanding sustainability reporting and various ESG compliance requirements, which will increase as government involvement in exports grows. Hence, environmental performance is increasingly becoming a prerequisite for market access rather than a means of differentiation. Numerous global tyre companies have publicly disclosed their objectives to reduce their carbon footprints and promote circularity in material sourcing. For example, some have set a target to increase the incorporation of sustainable materials in their products by at least 40% by the year 2030, while others have expressed their intention to transition entirely to renewable and recycled feedstock by 2045 (Bridgestone, 2023; Perto - Digital Accessibility, 2026). Under these circumstances, Sri Lanka needs to actively explore transitioning its conventional tyre offerings to greener alternatives. Therefore, Sri Lanka must implement strategic changes in raw material selection, energy sourcing, and other areas of solid tyre manufacturing to safeguard and strengthen this lucrative export market.

Based on the LCA results, carbon black, SBR, crumb rubber, and antioxidants such as 6PPD and TMQ are the primary contributors to most environmental impact categories, including human carcinogenic toxicity and global warming potential. In light of this finding, from a managerial perspective, these primary materials should be prioritised for modification or enhancement rather than pursuing unfocused, extensive sustainability initiatives. Bio-based synthetic rubbers instead of petroleum-based synthetic rubbers, bio-based fillers instead of

carbon black, self-healing materials instead of crumb rubber, bio-based fabrics and bio-based accelerators, recycled carbon black, and recycled fabrics are currently under consideration as green materials for green tyre manufacturing (Sampath et al., 2025). Substituting conventional raw materials with these cleaner materials would reduce toxicological risks and carbon emissions by a greater percentage, which will be particularly important for aligning with EU chemical regulations. Consequently, material substitution can yield multiple benefits for Sri Lankan solid tyre manufacturers, including environmental improvements and a strategic response to regulatory requirements.

In addition, the results indicate that grid electricity is a key driver of the resulting environmental impacts. The scenario analysis suggested that the transition to renewable energy sources (solar energy) could reduce numerous environmental impacts by significant percentages, for instance, global warming by approximately 20%. Amid rising carbon-related trade measures and buyer-driven sustainability requirements in the EU market, reducing carbon intensity can enhance the competitive position of Sri Lankan solid tyre manufacturers. EUDR is highly relevant to this industry, as natural rubber is one of its main raw materials. Rubber estates are highly monitored under it. The EUDR (Regulation (EU) 2023/1115) came into effect in June 2023. Its enforcement has been postponed twice, most recently through Regulation (EU) 2025/2650. It now takes effect on 30 December 2026 for large and medium operators, and on 30 June 2027 for micro and small operators. The delay does not change the core due diligence and traceability requirements. The Commission has stated it will not revisit the regulation, meaning the extra time is intended for preparation, not a delay in obligations. Therefore, after these specified dates, any product exported to the EU must be deforestation-free, traceable to the exact land where it was sourced, and legally produced under the source country's laws. Sri Lanka remains categorised as a low-risk country under the EUDR, reducing the need for risk assessments on the EU importers' side, but exporters must still submit detailed geolocation data and proof of legal land ownership for farms producing rubber. Although this process is simpler for large plantations, smallholder farmers—who manage 68.14% of the country's rubber cultivation—have not yet developed the capacity to meet these demands (TalkingEconomics, 2025). Sri Lankan solid tyre manufacturers source natural rubber from smallholder farmers and large estates, which could lead to future EUDR non-compliance issues and ultimately threaten the EU market for Sri Lankan solid tyres.

Sri Lankan solid tyres are currently outside the EU Carbon Border Adjustment Mechanism's scope. From January 2026, this mechanism will mainly cover cement, iron and steel, aluminium, fertilisers, hydrogen, and electricity. Its 2028 proposal aims to include steel- and aluminium-intensive downstream products. At present, the main carbon-related pressure on tyres comes from buyer demands and value-chain reporting, not from border taxes. The more immediate regulatory influence is the Ecodesign for Sustainable Products Regulation, which lists tyres as a key product group.

The Ecodesign for Sustainable Products Regulation (EU 2024/1781) provides a general framework, with specific requirements detailed through product-specific delegated acts. According to the ESPR and the Energy Labelling Working Plan 2025–2030 (COM(2025) 187, approved on 16 April 2025), tyres are classified as one of six priority product groups, alongside textiles, furniture, mattresses, iron and steel, and aluminium. The planned adoption window for delegated acts is around 2027, followed by an 18-month transition period. These delegated acts are expected to establish rules on durability,

recycled content, carbon disclosure, and a Digital Product Passport (Directorate-General for Environment, 2025).

Considering these outcomes, if solid tyre manufacturers act proactively, Sri Lanka can further secure and enhance its global positioning. Based on the findings of this study, a green solid tyre, a product with a reduced carbon footprint and minimized toxicological impacts, can be proposed, which needs further research. This positioning would cater to the accelerating demand for environmentally responsible products in the global market. By using LCA insights, companies can improve internal operations and communicate their environmental performance to buyers, reinforcing their value proposition in sustainability-sensitive markets.

CONCLUSIONS

This study offers a thorough cradle-to-gate Life Cycle Assessment (LCA) of solid tyre manufacturing in Sri Lanka, providing essential baseline data for one of the nation's most vital export-oriented industries. The results indicate that environmental impacts concentrate in specific inputs and processes, particularly the use of carbon black, synthetic rubber (SBR), recycled rubber (crumb rubber), and chemical additives, as well as in energy-intensive manufacturing stages. Among the impact categories, human carcinogenic toxicity, freshwater and marine water-related depletions, fossil resource scarcity, ozone formation (terrestrial ecosystems), terrestrial ecotoxicity, ozone formation (human health), terrestrial acidification, and global warming are identified as primary concerns, highlighting the significant environmental and human health implications associated with current production practices.

Beyond mere quantification, this study underscores the strategic importance of Life Cycle Assessment (LCA) as a decision-support tool under escalating global sustainability pressures. The identified environmental hotspots signal not only operational inefficiencies but also potential strategic risks, especially under European Union (EU) environmental regulations. Elevated carbon intensity could subject manufacturers to emerging carbon-related trade measures, while reliance on human labour and environmentally toxic chemicals may pose challenges under stringent chemical compliance frameworks. Therefore, companies should incorporate environmental performance into their core business strategy rather than treating it solely as a compliance exercise.

Material substitution and energy transition were identified as pathways to address the highlighted issues. Researchers have shown that reducing dependence on high-impact inputs such as crumb rubber, carbon black, SBR, and antioxidants by adopting cleaner or bio-based alternatives can significantly lower carbon emissions and toxicological risks. Likewise, shifting from conventional grid energy to a renewable source such as solar power can significantly reduce the overall carbon footprint and other major production impacts. These actions are environmentally beneficial and strategically vital for preserving access to export markets such as the EU, which prioritize sustainability. Based on these findings, positioning Sri Lanka as a green solid tyre manufacturer would create multidimensional advantages in global competition.

In conclusion, this study links environmental assessment with strategic planning by showing how LCA can guide sustainable decision-making in export-oriented industries. The results offer practical advice for manufacturers, policymakers, and stakeholders aiming to improve environmental performance and maintain long-term competitiveness. Future research should broaden the analysis to cover the entire life cycle of solid tyres, including distribution, use, and end-of-life stages, and investigate the economic

impacts of sustainability transitions to develop more comprehensive decision-making frameworks.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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The importance of green entrepreneurship in the context of green economy and sustainable development

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Keywords

*Green economy, green entrepreneurship,
green finance, renewable energy,
sustainable development*

ABSTRACT

Green entrepreneurship is becoming more and more seen as a tool that could connect environmental goals with business development; however, empirical evidence is in many instances still scattered between the global market and national policy and energy indicators. This study assesses the role, opportunities and constraints of green entrepreneurship through peer-reviewed literature and secondary institutional data (from LSEG, World Economic Forum, OECD, ICC and Sage, IRENA and ILO as well as official sources of Azerbaijan). Non-equivalent indicators are not compared, but rather the study uses structured descriptive benchmarking in the areas of market expansion, technology costs, SME finance and Azerbaijan's renewable-energy and policy environment. The data reveal that global green-economy market capitalisation surpassed US\$10 trillion in 2026, and that green revenues increased by 5.3% in 2025; the value of the green economy is projected to exceed US\$7 trillion by 2030 and is already more than US\$5 trillion. The share of SMEs stating that sustainability is important grew from 67% in 2024 to 70% in 2025, while green-finance applications and receipts stayed at 3% and 1% respectively. The share of renewables in Azerbaijan's overall energy supply increased from 1.3% in 2021 to 2.3% in 2025, with robust renewable energy development in solar and wind, and over AZN 34 million in concessional financing for 36 green projects. The results show that the market and technology momentum need to be supported by available finance, reporting ability, regulatory certainty, and specific government assistance to ensure that green-economy growth leads to greater entrepreneurial activity.

INTRODUCTION

The shift to a low carbon and resource efficient economy is transforming the rules of business game when it comes to the creation, financing and scaling of businesses. Demand for business models that create economic value and minimize environmental pressure has surged as a result of climate change, resource limitations, pollution and a new policy focus on sustainable development. Green entrepreneurship is within this transition as it involves product, service, or process that support environmental improvement and entrepreneurial opportunity recognition. The results of its work are therefore not only measured by profitability and growth but also by the positive impact achieved by environmental, energy and resource efficiency, emissions reduction, cleaner technologies and other sustainability outcomes (Domańska et al., 2018; Neumann, 2022).

Market evidence points to an increase in commercial space for the environment-oriented activity. The competitiveness of several low-carbon technologies, green revenues and the deployment of clean-energies have significantly improved and new opportunities have arisen in the areas of renewable energies, energy efficiency, waste management, circular production, mobility and environmental services. Meanwhile, SME's capacity to be a part of this transition is not consistent. Important for innovation and diffusion of green solutions, SMEs often suffer from barriers to finance, technical capacity, sustainability reporting, regulatory know-how and collateral.

These issues have a special relevance to Azerbaijan, where diversification, environmental quality, clean energy and private sector development become a growing part of national development priorities. Current debates tend to focus on the growth of the global green economy and on indicators of national transition, but often there is a gap between the global opportunity signals and the conditions which affect the development of entrepreneurial activity in the country. This study attempts to fill this void by systematically describing some key indicators of global markets and official evidence on green-project financing and renewable energy supply in Azerbaijan, along with some indicators for SME-financing. The goal is to find out where market dynamics are transforming into entrepreneurship, where they are still missing and which policy orientations are most relevant in strengthening green entrepreneurship in the national context.

LITERATURE REVIEW

Green entrepreneurship is considered as less generic form of sustainable entrepreneurship. Sustainable entrepreneurship aims to generate value in all three aspects of economy, society, and environment; and green entrepreneurship emphasizes more on environmental issues and opportunities. This is important because the environmental advantage is not a side effect of corporate responsibility but is a component of the value proposition, production process, chosen technology, or market served by the enterprise. Green entrepreneurship has therefore been empirically associated with

cleaner production, eco-innovation, renewable energy, resource efficiency, business models based on the circular economy and environmentally responsive business models (Domańska et al., 2018; Misztal & Kowalska, 2024).

There is no automatic link between green entrepreneurship and sustainable development. Entrepreneurship is a potential source of employment, innovation, and productivity; however, the environmental impact of entrepreneurship depends on the nature of what is being produced, how it is produced and what incentives guide the choice of what to produce and invest in. Green entrepreneurship is uniquely related to a sustainable-development outcome, as green entrepreneurs would react to a market failure and a still latent demand for environmental goods and services, as demonstrated by Neumann (2022). Recent studies also highlight that green entrepreneurship can contribute to the achievement of Sustainable Development Goals if the enterprises that drive it not only innovate but also are resource-efficient and have tangible environmental impacts (Onofrei et al., 2026; Chang et al., 2026).

The literature contains three groups of enabling factors. The first is that market demand and technological change can enhance green product/service profitability. As technology costs go down, so do entry barriers and the range of viable business models. Secondly, standards, procurement, tax treatment, licensing, disclosure requirements and access to public support are all ways in which policy and institutions impact green entrepreneurship. Predictable frameworks can promote longer-term investments, while regulatory uncertainty can create risk. Third, for SMEs, it is a question of finance and organisational capabilities. Smaller companies tend to face greater limitations in regards to available collateral, management capacity and transaction costs in the provision of sustainability information or in applying for dedicated financing (OECD, 2021, 2025).

The financing issue is not, therefore, merely one of a lack of interest. Evidence from international surveys shows that many SMEs consider sustainability to be a strategic element but very few SMEs make the leap from interest to formal green-finance applications and funding. This divergence is in line with the wider literature on information asymmetry and capability constraints in SME finance. It also emphasizes that supporting tools should consider not just the provision of financing, but also firms' capacity to design viable projects, report on environmental performance, and adhere to lender requirements (International Chamber of Commerce & Sage, 2025).

In Azerbaijan, the green entrepreneurship is closely related with national priorities in renewable energies, waste management, energy efficiency and economic diversification. This has been reinforced by recent uptick in renewable-energy supplies and green project concessional finance. A useful assessment, however, should not be based on a single numerical scale for global market capitalisation, cross-country SME surveys and national energy-balance indicators as these indicators measure different phenomena. Transparent benchmarking – whether the trends in the direction of global market change, SME financing conditions and the domestic transition indicators are mutually reinforcing and where the institutional bottlenecks are located – is therefore the best way to address this research gap.

MATERIALS AND METHODS

The research is descriptive and involves structured cross-level benchmarking and secondary data. The evidence base is summarised as a range of peer-reviewed studies together with institutional and official statistics. Global market indicators are sourced from LSEG and

World Economic Forum, while SME sustainability indicators and green-finance indicators are sourced from International Chamber of Commerce (ICC) and Sage reports, respectively. Evidence on SME support is drawn from OECD reports, and employment evidence is taken from International Renewable Energy Agency (IRENA) and the International Labour Organization (ILO) reports. The National indicators are based on the State Statistical Committee of the Republic of Azerbaijan, the Ministry of Economy, Azerbaijan Business Development Fund (ABDF) and the national development-priorities document.

The quantitative analysis is based on aggregate indicators published. The main time series for Azerbaijan are the following energy supply time series: total energy supply, hydropower, biomass and waste, wind, solar, total renewable-energy supply, and the renewable-energy supply as a share of the total energy supply for the 2021-2025 period. Any percentage-point changes are calculated directly from the published values, and are also presented as relative percentage changes. The study presents the following for the global green economy: market-capitalisation, revenue-growth, annual-value, projected value and technology-cost indicators for the reference years reported by the original sources. SME indicators are based on the 2024 survey results reported by ICC and Sage versus the 2025 survey results.

The benchmarking is not a direct statistical comparison but is rather an interpretive benchmarking. It is important to remember that the units and populations and denominators are different for global market capitalisation, annual value of the green economy, SME survey percentages, values of concessional loans and national energy-balance measures, so it would be misleading to use a single indicator. This analysis is based on a comparison of four dimensions: (1) market and technology opportunity, (2) SME access to green finance, (3) national renewable-energy and project-finance development and (4) implications for entrepreneurship. From these secondary data of aggregates no causal or inferential claims are made.

Data were reviewed against the institutional or official source mentioned in the reference and the terminology was standardised throughout the manuscript. In particular, the term 'SME' is used consistently to refer to small and medium enterprises, amounts of energy are provided in thousand tonnes of oil equivalent (thousand toe) and percentage changes are differentiated from percentage point changes. Limitations of the study include the uneven geographic coverage of data, the variation in survey construction, in the definition of indicators, and a lack of Azerbaijani firm-level microdata. These restrictions are taken into account in the interpretation of the results.

RESULTS AND DISCUSSION

Costs of technology, employment and global market growth.

The global evidence indicates that there is a sizeable and growing market for green products and services. The global market capitalisation of the green economy reached a milestone value of more than 10 trillion USD for the first time in 2026 (LSEG, 2026), while green revenues grew by 5.3% in 2025, the fastest pace since 2022. According to World Economic Forum, the annual Green Economy in the world is estimated to be more than US\$5 trillion and reach over US\$7 trillion by 2030 (World Economic Forum, 2025). Don't add up these measures; they look at various aspects of the market: market capitalisation is a valuation of the asset market while annual value or revenue indicates the economic activity over a period. But, as a whole, they provide signs of size and ongoing growth.

This opportunity signal is backed up by technology costs. Solar PV and lithium battery prices have dropped by approximately 90% since

2010 and made business models relying on distributed generation, storage, electrification and energy services more competitive (World Economic Forum, 2025). Social aspects also play a major role: in 2024, IRENA and ILO estimate that there will be at least 16.6 million jobs in the renewable energy sector worldwide (IRENA & ILO, 2026). But, these trends are relevant to entrepreneurs as declining technology prices can lower the capital costs of some activities, and market growth and job creation will increase the demand for complementary services, skills, maintenance, logistics, and digital solutions.

Table 1. Selected indicators of the global green economy

Indicator	Value	Reference period
Green-economy market capitalisation	> US\$10 trillion	2026
Growth in green revenues	5.30%	2025
Annual value of the green economy	> US\$5 trillion	2025 benchmark
Projected annual value	> US\$7 trillion	2030
Solar PV technology cost decline	~90%	Since 2010
Lithium-battery cost decline	~90%	Since 2010

Sources: LSEG (2026) and World Economic Forum (2025). Market capitalisation and annual market value are distinct indicators and are not directly additive.

SMEs and their sustainability and access to green financing.

The picture is different with the SME evidence: strategic interest is more strongly expressed than financial access. Across the ICC-Sage survey evidence, the share of SMEs stating that sustainability is central or important to their business increased from 67% in 2024 to 70% in 2025, while public disclosure of environmental performance increased from 24% to 30%. There was minimal growth in interest in green finance (26% to 27%). However, the percentage of those applying for green finance has remained steady, as has the percentage of those receiving it, at 3% and 1%, respectively (International Chamber of Commerce & Sage, 2024, 2025).

This results in a clear aspiration-finance gap. The SMEs interested in green finance were 24 percentage points higher than the SMEs that applied for green finance in 2025, while SMEs that applied for green finance were 26 percentage points more than those that had received finance in 2025. The reduction in the percentage of SMEs who reported having a formal sustainability-reporting system (21% to 8%) should be taken with a grain of caution, as the data are from two different report editions and could relate to shifts in the composition of the survey and/or the measure, in addition to actual behaviour. However, this trend aligns with OECD findings indicating that collateral, lack of expertise, information needs and access to finance are all restrictions that limit SME involvement in green investment (OECD, 2021, 2025).

Table 2. SME sustainability and green-finance indicators, 2024-2025

Indicator	2024	2025
Sustainability is central or important to the business	67%	70%
Publicly disclose environmental performance	24%	30%
Interested in green finance	26%	27%

Have a formal sustainability-reporting system	21%	8%
Applied for green finance	3%	3%
Received green finance	1%	1%

Sources: International Chamber of Commerce & Sage (2024, 2025).

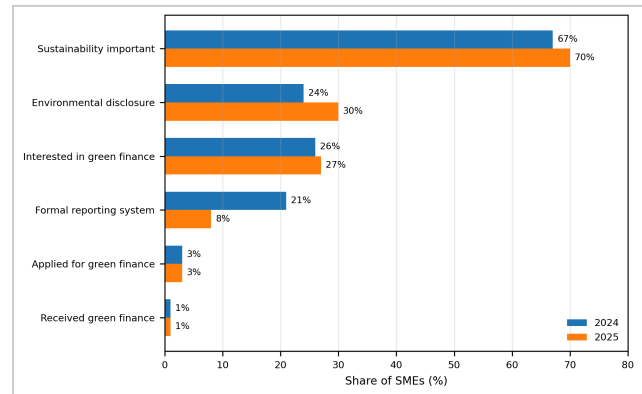


Figure 1. SME sustainability and green-finance indicators, 2024-2025, in comparison

Azerbaijan: policy support and financing for green projects and renewables.

The policy framework of Azerbaijan gives domestic foundation for the development of green entrepreneurship. The President of the Republic of Azerbaijan, 2021, in his speech 'Azerbaijan 2030: National Priorities for Socio-Economic Development' established the connection between competitiveness and private-sector development and a cleaner environment and a green-growth agenda. Waste processing, resource efficiency, transport, agriculture and energy are also identified as important areas of the green-economy transition by the Ministry of Economy (Ministry of Economy of the Republic of Azerbaijan, n.d.). Such priorities generate potential demand for solutions in the fields of renewable-energy services, energy efficiency, recycling, circular production, electric mobility and environmental technologies, which are entrepreneurial solutions.

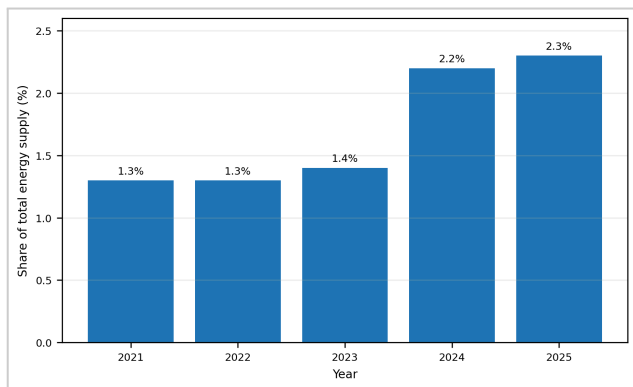
There are more signs of financing support. The Azerbaijan Business Development Fund has given over AZN 34 million in concessional loans to 36 green projects, reported the Azerbaijan Business Development Fund. The activities supported include solar energy, electric-vehicle charging infrastructure, plastics, metal, battery, glass, tyre, and other waste recycling (Azerbaijan Business Development Fund, n.d.). The importance of this support is not just the amount of loan volume; it shows that public finance is being applied to reduce barriers to entry in industries with potential environmental benefits and commercial returns that can appear on various time scales.

The official energy statistics indicate a similar change in the domestic energy mix. Total renewable-energy supply grew from 225.1 thousand toe in 2021 to 411.5 thousand toe in 2025 (+82.8%). Hydropower grew by 122.7%, wind grew by 87.3% and solar energy grew from 4.8 thousand toe to 51.6 thousand toe (a factor of 10.4 increase from a low base). Renewable energy share in total energy supply grew from 1.3% to 2.3% (+1.0 p. p.) (State Statistical Committee of the Republic of Azerbaijan, 2026). Although the contribution to the energy balance is still low, the acceleration from 2023 onwards is of economic importance, as it increases the market for installation, engineering, maintenance, financing, digital monitoring and various other services.

Table 3. Selected renewable-energy supply indicators in Azerbaijan, 2021 and 2025

Indicator	2021	2025
Total energy supply, thousand toe	17,566.6	17,857.8
Hydropower, thousand toe	109.8	244.5
Biomass and waste, thousand toe	102.6	100.6
Wind power, thousand toe	7.9	14.8
Solar power, thousand toe	4.8	51.6
Total renewable supply, thousand toe	225.1	411.5
Renewables in total energy supply, %	1.3	2.3

Source: State Statistical Committee of the Republic of Azerbaijan (2026), Energy of Azerbaijan 2026. The table reports the endpoints of the 2021-2025 series; Figure 2 presents the annual renewable-share trajectory.

**Figure 2.** Renewables' share in energy supply (Azerbaijan, 2021-2025)

Cross-level synthesis and policy implications.

Today, the lack of a green market signal is no longer the main hurdle, according to the evidence from the cross-level. The growth of products and services in the global market and the decreasing costs of technology suggest that products and services are becoming more marketable. The problem seems to be in the transition of this opportunity to investable SME projects. The interest in green finance is still significantly larger than the amounts actually received, both at international and domestic levels; and the participation of firms and private finance in green finance is still in its infancy in the domestic context. This aligns with research that considers green entrepreneurship not just as something to do with motivation but also market opportunity, institutional quality and financing mechanisms, and enterprise capabilities (Neumann, 2022; Onofrei et al., 2026).

The four signals that emerge from cross level benchmarking are the same. On one hand, the opportunity environment is very favorable due to the growth of the global green-economy and the reduction of technology costs; on the other hand, Azerbaijan demonstrates a very high growth rate of solar and wind energy supply and at the same time is at the initial stage of their transition in terms of the share of renewable energy in the overall energy supply. Second, based on the international SME evidence, there is strong interest in sustainability, but low uptake of green finance at the firm level and applications for such financing; in the domestic context, concessional green-project financing is available, but it is not possible to infer uptake of financing at the company level from the aggregate programme data. Third, the green investment and employment in the field of renewable energy continue to grow globally, while Azerbaijan's renewable energy share rose from 1.3% in 2021 to 2.3% in 2025. Fourth, evidence from around the world and evidence from the UK shows that finance,

reporting capacity, predictable regulation, advisory support and clear eligibility conditions are all key in moving green opportunities into enterprise-level activity.

Thus, the area of policy optimisation for Azerbaijan should be the link between entrepreneurs and finance. Some practical solutions are the standardisation of green project eligibility criteria, streamlined documentation for smaller companies, advisory help with environmental and financial reporting, credit-enhancement or guarantee mechanisms as applicable, and better knowledge on the available incentives. It also indicates that business ecosystems around renewable energy should be supported in addition to the generation assets, as these have seen significant growth in recent times, particularly in the solar and wind energy sectors. It is possible to expand the entrepreneurial opportunities that come with the transition by introducing local engineering, maintenance, energy-management software, recycling, charging infrastructure and efficiency services.

However, the evidence elicits cautious interpretation of scale as well. In relative terms, however, Azerbaijan's renewable share increased significantly and in 2025, renewables made up 2.3% of all energy supplies. Similarly, the presence of green loans on concession is not sufficient to proof of access to green loans for SMEs. For this reason, further empirical studies should be conducted based on the firm-level data to test what financing, regulatory and capability factors have the strongest effect on the adoption of green technologies and the access to finance in Azerbaijan.

CONCLUSIONS

This study demonstrates that the market and technology environment is conducive to green entrepreneurship but that institutional and financial environment can be a barrier for the companies to exploit these opportunities. The global green-economy market capitalisation has surpassed US\$10 trillion, green revenues are still growing, and the prices of important green technologies, including solar PV and batteries have dropped substantially. Meanwhile, evidence from the SME survey shows a longstanding disconnect between sustainability goals and green financing for SMEs. Azerbaijan has a more favorable climate for environmentally oriented business activity, thanks to the national policy priorities, green project financing with concession contracts and a growth in solar and wind energy. Renewable energy is still a small component of total energy provision and the available overall figures do not indicate to what extent green financing penetrates individual SMEs. The key policy messages are that support for green entrepreneurship should be based on a combination of predictable regulation, accessible and tailored finance, hands-on reporting and advisory services, and an ecosystem that facilitates renewable energy, circular production, waste management and resource efficiency. The study is a contribution in linking global opportunity indicators to national transition evidence without assuming that non-equivalent measures are directly comparable. Future studies should focus on assessing the causal links between policy support, access to finance, green innovation and enterprises' performance based on firm level and sector level data in Azerbaijan.

AUTHOR CONTRIBUTIONS

All authors contributed to the development and review of the manuscript and approved the final version for submission. Detailed CRediT roles may be confirmed by the authors during final production if required by the journal.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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DATA AVAILABILITY

This study is based exclusively on secondary data and published institutional sources. The data analysed in the manuscript are publicly available from the sources cited in the reference list.

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Adoption of improved maize seeds and Sustainable Agricultural Intensification among rural households in Cameroon

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Keywords

*Cameroon, improved seeds, maize, rural
households, Sustainable Agricultural
Intensification*

ABSTRACT

In Cameroon, the sustainable intensification of agricultural production is essential to addressing environmental, economic and social challenges, particularly in rural areas where natural resources are under significant pressure and agricultural yields are low. Improved seeds clearly contribute to enhancing agriculture by requiring fewer inputs and promoting sustainability. Households that adopt these seeds benefit from increased yields and reduced crop losses, transforming subsistence farming in a sustainable way. This study analyses the impact of improved seeds on the sustainable intensification of maize production, which is the main crop for intensification among rural households in Cameroon, using data from the 2017 Cameroon Comprehensive Food Security and Vulnerability Analysis. Descriptive statistics, propensity score matching (PSM) and stochastic frontier analysis (SFA) indicate that 60.35% of the 4,101 households practise intensive maize cultivation, while 39.65% do not. Among those growing maize, 30.1% use improved seeds, yielding 344.45 kg/ha compared to 291.675 kg/ha for non-improved seeds. Adopting improved seeds thus increases the probability of achieving efficient and sustainable production by 21.8%. Technical, allocative and economic efficiencies are 0.52, 0.815 and 0.709, respectively. This suggests that, despite the risks of inefficiency associated with the overuse of fertilisers, pesticides and labour, improved seeds can increase yields and reduce input waste. Therefore, it is essential that public policy priorities focus on encouraging the adoption of improved seeds, providing market support, and creating sustainable seed systems.

INTRODUCTION

Processes of agricultural intensification, which began in Cameroon as part of government programmes in the 1970s, are now integrated into agricultural development strategies such as the National Rural Development Strategy and the National Sustainable Development Strategy (SDSR/PIA, 2020). These strategies acknowledge the significant potential of rural areas for increasing agricultural production, particularly maize production. This crop has been cultivated extensively in Cameroon in recent years due to the availability of arable land and the potential for irrigation (Guibert et al., 2016; SDSR/PIA, 2020; World Bank, 2020). The country has approximately 7.2 million hectares of land, but only 1.8 million hectares are currently cultivated. The potential for irrigation is estimated at 240,000 hectares (World Bank, 2020). Cameroon produces an average of 2.36 million tonnes of maize per year, with nearly 2.75 million rural households depending on this crop for their income. These households are seeking to increase their production. Furthermore, the diversity of agroecological zones makes intensive maize cultivation favourable, and rural households have a strong incentive to do so. This practice offers a vital way to boost their earnings, guarantee their food security and ease the strain on land (Guibert et al., 2016).

Although maize production in Cameroon has increased by around 4.4% per year, supply remains insufficient to meet the rapidly growing

domestic demand of over 2.8 million tonnes (SDSR/PIA, 2020; NIS, 2025). While it would be possible to increase the area under cultivation, this would seriously harm local communities and exacerbate the socio-environmental damage already evident in rural areas. This damage is primarily caused by erratic rainfall and prolonged periods of drought resulting from climate change, as well as the loss of soil fertility (WFP, 2017; World Bank, 2020). Indeed, infertile soils currently account for 25–30% of land suitable for maize cultivation in Cameroon, resulting in significantly lower yields. Furthermore, pressure on natural resources could increase considerably due to population growth and high demand for maize for consumption. This would exacerbate the economic and social vulnerabilities of rural populations who depend on this crop (World Bank, 2020).

Since 1990, the traditional approach of intensifying arable land has given way to seed programmes that aim to increase maize yields per unit area by ensuring seed security (Ball, 2016). Since then, public policies in Cameroon have encouraged the adoption of improved seeds in order to meet the growing demands of sustainable agriculture (De La Paix Bayiha et al., 2020). These state-managed programmes have increased maize yields by 10–30% since 2005, thereby promoting the intensification of this crop (MINADER, 2020). However, the adoption of improved maize seeds presents challenges in some rural areas due to inefficient supply chains, which constitute a significant barrier to intensifying this crop among rural households (Djamen,

2016; Ball, 2016; Takam-Fongang et al., 2019). According to the World Bank (2020), rural households in Cameroon face numerous obstacles preventing them from increasing production, food security and income, particularly due to limited access to improved seeds. In addition to this, sustainable agricultural intensification requires greater financial investment, a readily available labour force and improved knowledge and skills regarding seeds.

There are also concerns regarding the predominant maize farming systems in rural areas of Cameroon. These systems rely heavily on limited natural resources and demonstrate a low rate of improved seed adoption (Meughoyi, 2018; Takam-Fongang et al., 2019). This is leading to slower growth in agricultural yields, the resurgence of environmental problems and constraints on land and water that are hindering the long-term intensification of maize cultivation. Furthermore, rural development initiatives often overlook resource sustainability and improved agricultural practices, and access to improved seeds remains a major obstacle. However, the long-term intensification of maize cultivation in Cameroon depends on adopting inputs such as improved seeds, fertilisers, and modern techniques, which can increase yields beyond those achieved through traditional farming methods (Guibert et al., 2016). Consequently, in rural areas where access to improved seeds is limited, further intensification yields diminishing marginal returns that are often below the potential yields for maize (Ball, 2016).

These findings therefore prompt this study to examine the role of improved seeds in the sustainable intensification of agriculture among rural households in Cameroon. Using maize cultivation as a case study, the study will assess the economic, social and environmental effectiveness of this approach. With this in mind, the study formulates the following analytical hypothesis: improving the conditions for adopting improved maize seeds in Cameroon would enable rural households to produce goods efficiently and sustainably. This would make them more technically proficient in terms of agricultural intensification than their counterparts.

This study examines this relationship in five sections. It highlights the relevant conceptual and theoretical links and reviews the empirical research on sustainable agricultural intensification in Cameroon. It describes the methodology adopted, then presents and analyses the results obtained. Finally, the study concludes with an analysis of the implications for economic policy.

LITERATURE REVIEW

The concept of Sustainable Agricultural Intensification

Pretty et al. (2011) popularised the concept of “Sustainable Agricultural Intensification” to describe the goal of boosting agricultural production while safeguarding the environment and rural economies. This generally involves making the most of natural, social, and human capital while using the best available technologies and inputs to minimise or eliminate environmental damage. Similarly, Wezel et al. (2015) define sustainable agricultural intensification as increasing production from the same area of land while conserving resources, reducing negative environmental impacts, and enhancing natural capital and the flow of ecosystem services. In summary, sustainable agricultural intensification practices aim to improve the productivity and resilience of agricultural production systems while conserving natural resources. These practices involve adopting certain inputs and integrating multiple technologies, which together constitute a broader concept of sustainable intensification (Vanlauwe et al., 2014; Kassie et al., 2015).

Wezel et al. (2015) identified three main approaches to sustainable agricultural intensification: Socio-economic intensification promotes the development of innovative and sustainable institutions within farms, communities, markets, and rural areas. Ecological intensification is exemplified by agricultural practices that enhance the mutual benefits between crops, such as integrated pest management, conservation agriculture, and organic farming. Genetic intensification involves preserving beneficial genes and combining them with other complementary genes from close or distant relatives to improve the yield of cultivated varieties. The latter approach involves adopting improved seeds that are more productive, disease-resistant and suited to local conditions.

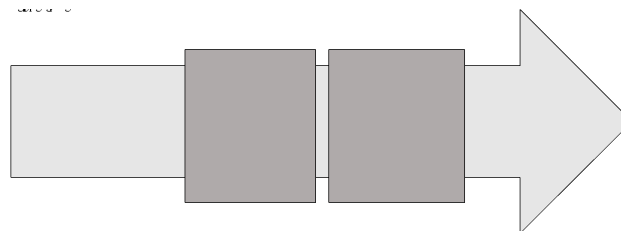


Figure 1. Approaches to Sustainable Agricultural Intensification.

Figure 1 shows the two main approaches to achieving Sustainable Agricultural Intensification: ecological intensification, based on ecological agricultural processes, and genetic intensification, which relies on modern plant breeding and improved seeds. Adopting improved seeds helps achieve the objective of sustainability by making farming more productive with fewer inputs (Louwaars & de Boef, 2012; McGuire & Sperling, 2016). Rural households experience the benefits almost immediately, as increased yields and reduced crop losses transform agriculture, moving it from a subsistence to a developmental phase. Improved seeds can also help agriculture adapt to constantly evolving climate threats and stresses, thus meeting environmental requirements (Sharrock, 2016).

Theoretical interpretation of the role of improved seeds in Sustainable Agricultural Intensification

The theoretical literature on the role of improved seeds in Sustainable Agricultural Intensification tends to focus on three areas: (i) their impact on productivity, (ii) their impact on natural resource management and (iii) their impact on the institutional framework of rural households (Pretty et al., 2011; Tittonell, 2014). All of these approaches are theoretically rooted in economic principles, the natural sciences and agroecology. However, these fields are fundamentally different: economists focus on economic changes, while agroecologists are concerned with environmental consequences and the long-term relationship between households and their environment.

From an economic perspective, the role of improved seeds in sustainable agricultural intensification is part of a broader theoretical debate about the need to increase agricultural production to meet the growing needs of rural populations (Turner & Wiber, 2009). Pingali et al. (1987) demonstrated that modest agricultural growth could sustain steady population growth if farmers adopted technical innovations. Consequently, in areas subject to high agricultural pressure, where production resources are dwindling — as is generally the case in rural areas — a more intensive approach to agricultural practices is required. This involves utilising intensification factors, such as improved seeds, to increase crop rotation and boost the amount of labour and technological resources devoted to intensifying agricultural production (Turner & Wiber, 2009).

For its part, ecological intensification aims to increase the yield potential of major crops and reduce yield variability by using precision farming techniques based on scientific advances in agricultural science

(Petersen & Snapp, 2015). It is therefore considered a way of increasing agricultural production while reducing dependence on external resources by utilising the ecological processes that sustain and regulate the primary productivity of agricultural ecosystems (Tittonell, 2014). The growing interest in improved seeds appears to be a response to the negative environmental and social impacts associated with intensive production strategies (Pretty et al., 2011; Garnett et al., 2013; Sharrock, 2016).

Adoption of improved maize seeds and intensification of maize production in Cameroon

Empirical literature (Ntsama & Kamgnia, 2008; Mabah Tene et al., 2013; Meughoyi, 2018; Takam-Fongang et al., 2019) clearly shows that rural households in Cameroon's adoption of improved maize seeds is influenced by various factors. These include the age and level of education of the household head, household size, experience, farm size, market access, the farmer's perception of high-quality maize seed characteristics, yield and profitability, membership of a farmers' association, attitude towards risk and access to credit.

Mabah Tene et al. (2013) attribute the low uptake of improved maize seeds in Cameroon to a mismatch between the supply of seeds and production prospects, and farmers' actual needs. This mismatch can be explained by several key factors: limited access to extension services; low levels of education in certain rural areas; a lack of adaptation to the local context; socio-economic constraints linked to the cost of inputs; labour constraints; and market risks. These factors do not always correspond to farmers' investment capacity and actual needs. Ntsama and Kamgnia (2008) explain that adopting improved maize seeds often requires additional investment, and that farmers with limited financial resources are negatively affected by difficulties in accessing credit when trying to adopt these seeds. Conversely, cooperative or farmers' organisation membership greatly facilitates access to finance and credit for seeds.

Both Andrianarison et al. (2021) and Mveng et al. (2023) have demonstrated that the age of the household head, level of education, size of the family labour force, area under cultivation, contact with extension workers, membership of a farmers' organisation, household income, and availability of improved seeds significantly influence their adoption. The main barriers to adopting improved seeds are high prices, insufficient resources, a lack of information, distance from markets and seed unavailability.

In terms of sustainable agricultural intensification, the adoption of improved seeds can be used as an example (De La Paix Bayiha et al., 2020). The channels through which improved seeds influence agricultural intensification are technological, economic and institutional, and are specific to each household (De La Paix Bayiha et al., 2020; Andrianarison et al., 2021). For example, Meughoyi (2018) demonstrated in his research that the adoption of improved maize seeds by Cameroonian farmers was associated with increased productivity. The potential productivity of farmers who adopt improved maize varieties is 1.42 times higher than that of farmers who adopt conventional varieties. Similarly, the productivity gap between adopters and non-adopters is estimated at 0.351 kg/ha. Meughoyi (2018) therefore concludes that adopting improved varieties leads to the intensification of maize production in Cameroon. A study by Takam-Fongang et al. (2019) also revealed that 47.65% of farmers in central Cameroon had adopted improved maize varieties, achieving yields of 1,938.04 kg/ha compared to 1,263.17 kg/ha for non-adopters. However, despite this adoption, actual yields remain below potential, with 68.82% of farmers reusing their seeds.

However, while the impact of improved maize varieties on agricultural yields has been studied, the role of improved seeds in the sustainability of agricultural intensification in Cameroon has not yet been examined in a large-scale study. This is precisely the gap that the present study aims to fill.

MATERIALS AND METHODS

Nature and source of the data

The data used in this study were obtained from secondary sources and taken from the most recent Comprehensive Cameroon Food Security and Vulnerability Assessment (CFSVA). This national study, conducted in 2017 by the World Food Programme in partnership with the Cameroonian government, assessed food insecurity and household vulnerability in Cameroon. The study aimed to assess households' access to production resources, particularly improved seeds, identify those most vulnerable to climate shocks, and provide data to inform development policies (WFP, 2017). Based on these objectives, a random sample of 4,101 rural households was selected, taking into account the adoption of improved maize seeds and increases in maize yields.

Measurements of key variables in the analysis

In this study, the adoption of improved maize seeds and the intensification of maize production are the two main explanatory variables. A household is classified as an "adopter" if it used improved maize seeds at the time of the survey and as being in the "intensification" phase if it increased its maize production during the survey year (Shiferaw et al., 2014).

In non-experimental studies, assessing the impact of improved seeds on agricultural production usually involves addressing selection bias among households, given that adoption or non-adoption is not random. This method provides an unbiased and consistent estimate of the impact of adoption. Adopters and non-adopters of improved seeds with similar characteristics are therefore assigned a propensity score (PSM), which reduces bias associated with observed variables (Rosenbaum & Rubin, 1983).

For the output variables, this study examines the Technical Efficiency (TE), Allocative Efficiency (AE) and Economic Efficiency (EE) of households involved in maize production. TE, AE and EE scores range from 0 to 1: a score of 1 indicates maximum efficiency and the optimal use of resources, while a score of 0 represents a complete lack of efficiency in production. Therefore, intermediate values suggest a combination of efficiency and inefficiency, as well as the potential for increased agricultural production. Higher TE, AE and EE values suggest intensified production.

Framework for estimating the empirical model

The econometric estimation framework used in this study employed a specific Stochastic Frontier Analysis (SFA) to calculate the TE, AE and EE indices. The results of this analysis are presented in the section on the empirical strategy.

Technical inefficiency was estimated using a stochastic frontier and then incorporated into a regression model to identify the influencing factors. However, missing variables affected this procedure, contradicting the assumption regarding the distribution of inefficiency effects. To address this issue, this study applied Maximum Likelihood Estimation (MLE), as recommended by Kumbhakar and Lovell (2003), alongside Least Squares Estimation (LSE) to estimate the stochastic frontier and inefficiency model simultaneously.

The SFA, developed by Aigner et al. (1977), is a parametric method used to assess efficacy based on a specific mathematical formula.

$$Y_i = f(x_i, \beta) \exp(v_i) \exp(-u_i) \quad (1)$$

where y_i is the output value of the i -th household, x_i is a vector of inputs, β is a vector of parameters to be estimated, and $v_i \sim N(0, \sigma_v^2)$ and $u_i \sim N + \left[f(u, \alpha), \varphi_u^2 \right]$ are the random error and inefficiency terms, respectively.

Battese and Coelli (1995) describe the estimation of the components of technical efficiency based on Equation 1 as follows:

$$u_i = f(u_i, \alpha) \quad (2)$$

A combination of statistical tools was used for the analysis, including descriptive statistics, percentages and econometric models. A probit regression analysis was performed to identify the factors influencing the intensification of maize cultivation in rural Cameroon. The analysis focused on production and cost functions in order to evaluate the efficiency of this agricultural intensification.

Mathematically,

$$l_n(1/1 - p) = bo + b_1X_1 + b_2X_2 + b_3X_3 \dots + b_nX_n \quad (3)$$

Where X_i is the combined effect of X explanatory variables that encourage or discourage households' decision from increasing their production.

Similarly,

$l_n(1/1 - p)$ = the logarithm of the probability of farming households deciding to intensify maize production by adopting improved seeds.

$X_1 \dots X_i$ are the factors that encourage or hinder rural households from intensifying their production. These factors are defined as follows: access to information, use of labour, use of improved seeds, proximity to a market, total land area, expenditure on food, non-food expenditure, expenditure on agricultural inputs, and the household's financial situation (wealth).

The maize production frontier function is estimated using a linear model.

$$l_n Y_i = \beta_0 + \beta_1 l_n X_{1i} + \beta_2 l_n X_{2i} + \beta_3 l_n X_{3i} + v_i - u_i \quad (4)$$

Where,

Y_i = production quantity per hectare in kg for the i -th household; X_{1i} = seeds in kg from the i -th household; X_{2i} = labour in man-days for the i -th household; X_{3i} = inputs (fertilisers and pesticides) in kg for the i -th household; β = a vector of unknown parameters to be estimated. v_i is the random variable (stochastic error term) which is assumed to be independently and identically distributed as $N(0, \sigma_v^2)$; u_i is the non-negative estimate of the farm's technical inefficiency.

Similarly, the selected marginal cost function is:

$$l_n C_i = \beta_0 + \beta_1 l_n Y_i + \beta_2 l_n X_{1i} + \beta_3 l_n X_{2i} + \beta_4 l_n X_{3i} + v_i + u_i \quad (5)$$

Where,

C_i = total household expenditure on agricultural production Y_i = value of production per kg for the i -th household, X_{1i} = cost of seeds for the i -th household, X_{2i} = wages for labour provided by the i -th household, X_{3i} = input costs for the i -th household, β_0 = constant; $\beta_1 - \beta_4$ = cost function parameters; l_n = natural logarithm.

The term "error", which consists of two parts ($\varepsilon_i = v_i + u_i$), is defined as follows: v_i = random error caused by statistical noise,

weather conditions, illness, etc., which are beyond the control of households; u_i = risk (economic inefficiency) arising from household characteristics.

The framework for assessing technical, economic and allocative efficiency is therefore as follows:

$$a) TE_i = \frac{y_i}{\hat{y}_i} = \frac{Y_i}{f(x_i, \beta) \exp(v_i)} = \exp(-u_i) \quad (6)$$

$$b) EE_i = \frac{C_i}{\hat{C}_i} = \frac{C_i}{f(x_i, \beta) \exp(v_i)} = \exp(-u_i) \quad (7)$$

$$c) AE = EE/TE \quad (8)$$

Where,

Y_i is the observed output subject to inefficiency; y_i corresponds to the frontier output subject to inefficiency; X_i are the independent variables, u_i = error term. Total production cost (C_i) is relative to the actual total production cost C_i^* .

RESULTS AND DISCUSSION

Summary of descriptive statistics

Of the 4,101 households surveyed, 60.35% (2,475 households) grow maize intensively, while 39.65% (1,626 households) do not. Of those that do, 30.1% (745 households) use improved seeds, while 69.9% (1,730 households) do not. Table 1 provides the definitions and summary statistics for the variables used in the analysis.

Table 1. Descriptive statistics for the variables used in the study

Variable	Description	Mean	Std dev.
Age (age group 1)	1 = ≤30 years old ; 0 = otherwise	0.106	0.308
Gender (male)	1 = yes ; 0 = otherwise	0.837	0.37
Access to information	1 = yes ; 0 = otherwise	0.626	0.484
Cooperative	1 = member ; 0 = otherwise	0.037	0.189
Production	Average maize yield/ household (kg)	483.659	1006.064
Quantity of seeds	Quantity of seeds used/ household (kg)	27.791	57.13
Labour use	1 = use of external labour; 0 = otherwise	0.187	0.39
Quantity of inputs	Quantity of fertiliser & pesticides used/ household (kg)	226.248	441.064
Level of education (Higher)	1 = Higher education qualification; 0 = otherwise	0.019	0.135
Fishing and livestock	1 = yes ; 0 = otherwise	0.496	0.5
Household size (average size)	1 = ≤5 people; 0 = otherwise	0.209	0.407
Area 1	1 = Farming a plot of land ≤ 1ha ; 0 = otherwise	0.309	0.462
Area 2	1 = Farming a plot of land 1ha ≤ 2ha ; 0 = otherwise	0.358	0.48
Total areas	Total operational area/ household (ha)	1.897	1.494
Distance from the market	1 = Close to a market; 0 = otherwise	0.197	0.398
Expenditure on inputs	Household expenditure on inputs and pesticides (FCFA)	16675.198	58408.959

Variable	Description	Mean	Std dev.
Cost of seeds	Household expenditure on seeds (FCFA)	2568.752	9640.731
Labour expenses	Household's daily labour in exchange for food (%)	12.876	11.797
Consumption expenditure	Total household expenditure on consumption (FCFA)	131,093.05	304,103.78
Expenditure on food	Food expenditure/ household's own production	39.802	17.115
Non-food expenditure	Total consumption expenditure/ household, spent on non-food items	0.007	0.039
Household wealth	1 = "non-poor"; 0 = otherwise	0.202	0.301
Total agricultural expenditure	Expenditure on agricultural production (FCFA)	25,736.689	96,081.75
Use of improved seeds	1 = yes; 0 = otherwise	0.301	0.459

Source : Author's calculations

The majority of households that grow maize – 83.7% – are headed by men over the age of 30. Only 19.1% of these household heads have a university education, and around 21% of these households are medium-sized (six to eight people) and own around two hectares of arable land. However, the majority often farm on less than one hectare (20.2%). Some of these non-poor households (30.1%) are located far from markets and have limited access to credit (19.4%), but enjoy satisfactory access to information (62.6%). The average cost of maize seeds is 2,568.75 CFA francs (4.56 US dollars), while the cost of other inputs amounts to 16,675.20 CFA francs (29.62 US dollars). Furthermore, only 3% of household heads belong to a cooperative, and households employ barely 1% of external labour. The average production per household is 483.65 kg, with 27.79 kg of seeds and 226.25 kg of other inputs used. Around 49.6% of households diversify their activities by engaging in fishing and livestock farming. Finally, analysis of agricultural expenditure (an average of 25,736.69 CFA francs, equivalent to 45.71 US dollars) and household consumption expenditure (an average of 131,093.05 CFA francs, equivalent to 232.85 US dollars) illustrates the intensification of maize production.

Factors influencing rural households in Cameroon to adopt improved maize seeds

The validated regression model (pseudo-R-squared= 0.037) includes 12 independent and 1 dependent variable relating to the adoption of improved seeds. Eight of these variables positively influence the adoption of these seeds.

Table 2. Characteristics of the adoption of improved maize seeds in rural areas of Cameroon

Dependent variable: Use of improved seeds	Probit coefficients	Marginal effects
Age (age group 1)	0.138** (0.0681)	0.0461** (0.0234)
Gender (male)	0.227*** (0.0645)	0.0693*** (0.0185)
Access to credit	0.108* (0.0590)	0.0354* (0.0198)
Access to information	0.273*** (0.0447)	0.0866*** (0.0139)
Cooperative	0.216* (0.124)	0.0739* (0.0445)
Level of education (Higher)	0.397***	0.142**

Dependent variable: Use of improved seeds	Probit coefficients	Marginal effects
	(0.153)	(0.0587)
Fishing and livestock	0.130*** (0.0435)	0.0418*** (0.0140)
Household size (average size)	-0.163*** (0.0541)	-0.0508*** (0.0163)
Area 1	-0.306*** (0.0553)	-0.0950*** (0.0165)
Area 2	-0.193*** (0.0519)	-0.0610*** (0.0161)
Distance from the market	-0.158*** (0.0531)	-0.0494*** (0.0161)
Consumption expenditure	1.25e-07** (6.28e-08)	4.03e-08** (2.03e-08)
Constant	-0.892*** (0.0812)	
Observations	4101	4101
Mean dependent variable	0.265	
Pseudo r-squared	0.037	
Chi-square	174.514	

Note: Error terms in brackets *** p<0.01, ** p<0.05, * p<0.1

Source: Author's calculations

An analysis of the estimates in Table 2 shows that the variables relating to access to credit and cooperative membership are significant at the 1% level, while age, level of education, and consumer expenditure are significant at the 5% level. The main factor determining the adoption of improved seeds is level of university education, accounting for 14.2%. Similarly, gender, access to information, and fishing and livestock farming practices are significant factors, accounting for 10%. Conversely, household size, cultivated area and distance from the market negatively affect the adoption of these seeds. For instance, households located further from markets are less likely to adopt improved seeds, as those in closer proximity benefit from the free flow of information. This enables them to increase their incomes through selling their produce and engaging in non-agricultural activities (Tadesse & Bahigwa, 2015). However, proximity to markets for inputs and raw materials reduces uncertainty and offers greater flexibility in the face of production fluctuations, enabling rural households to access improved seeds (Teklewold et al., 2013; Khonje et al., 2018).

These findings are consistent with those of Nkurunziza et al. (2021) and Ngango et al. (2022), who found that the adoption of sustainable agricultural intensification practices is influenced by factors such as education, farm size, livestock ownership, group membership and agricultural extension services, as well as environmental conditions such as soil type and climate. Economic factors such as crop yields, household income and expenditure also influence sustainable agricultural intensification. Furthermore, the findings partially corroborate the work of Ntsama and Kamgnia (2008) and Mabah et al. (2013), which indicates that rural households in Cameroon adopt improved maize varieties depending on factors such as location, area under cultivation, relations with extension services, level of education, household size, and membership of agricultural organisations. Medium-sized rural households, which often lack labour for agricultural work, tend to opt for improved seeds as a means of compensating for this shortfall (Feder et al., 1985; Mwangi & Kariuki, 2015). The sex ratio and level of education also appear to significantly influence this process: men have better access to food production resources (Mwangi & Kariuki, 2015), and a high level of education

enables them to make better decisions based on available information, deriving the greatest benefit from adopting these seeds (Mwangi & Kariuki, 2015). Finally, adopting improved seeds becomes more challenging with age as people tend to adhere to established practices as they grow older (Feder et al., 1985; Mwangi & Kariuki, 2015).

Factors influencing sustainable intensification of maize production in rural Cameroon

When used appropriately, the binary Probit model explained 60.82% of the observed variation in household behaviour regarding the intensification of maize production in rural areas of Cameroon (see Table 3).

Table 3. Characteristics of sustainable maize production intensification in rural areas of Cameroon

Dependant variable: Production	Probit coefficients	Marginal effects
Access to information	0.158*** (0.0439)	0.0610*** (0.0169)
Labour use	0.143** (0.0589)	0.0541** (0.0219)
Use of improved seeds	0.218*** (0.0474)	0.0823*** (0.0175)
Distance from the market	-0.167*** (0.0485)	-0.0647*** (0.0190)
Total area	0.0271** (0.0138)	0.0104** (0.00530)
Expenditure on food	-0.00425*** (0.00116)	-0.00163*** (0.000446)
Non-food expenditure	-1.527*** (0.449)	-0.587*** (0.172)
Expenditure on inputs	2.425*** (0.434)	0.931*** (0.166)
Household wealth	-0.247*** (0.0447)	-0.0955*** (0.0173)
Constant	0.319*** (0.0674)	
Observations	4094	4094
Mean dependent variable	0.604	
Pseudo r-squared	0.039	
Chi-square	216.258	

Note: Error terms in brackets *** p<0.01, ** p<0.05, * p<0.1

Source: Author's calculations

Thus, access to information, labour utilisation, adoption of improved seeds, total cultivated area, and input expenditure all positively impact the intensification of maize cultivation. For instance, investing in fertilisers and pesticides alongside the use of improved seeds increases the likelihood of intensifying maize production by 93.1%.

Estimates of propensity scores

The impact of improved seeds on the sustainable intensification of maize production by rural households is assessed by taking all observable covariates influencing their use into account.

Table 4. Propensity scores for adopting improved maize to achieve sustainable intensification in rural areas of Cameroon

Variable	Coefficient	Std. error	Estimation (z)
Age (age group 1)	0.135	0.068	1.980**
Gender (male)	0.232	0.064	3.600***
Access to credit	0.111	0.059	1.880*
Access to information	0.281	0.045	6.300***
Cooperative	0.222	0.123	1.800*

Variable	Coefficient	Std. error	Estimation (z)
Fishing and livestock	0.129	0.043	2.970***
Household size (average)	-0.159	0.054	-2.940***
Area 1	-0.304	0.055	-5.500***
Area 2	-0.192	0.052	-3.710***
Distance from the market	-0.159	0.053	-3.000***
Consumption expenditure	0.000	0.000	2.070**
Constant	-0.895	0.081	-11.030***
Log likelihood	-2288.648		
Observations	4101		
Model's X ²	167.80		
Prob > chi2	0.0000		
Pseudo r-squared	0.0354		

Note: Error terms in brackets *** p<0.01, ** p<0.05, * p<0.1

Source: Author's calculations

Table 4 analyses various factors influencing the adoption of improved maize seeds for sustainable intensification in rural areas of Cameroon, such as the age and gender of the head of household, access to credit and information, membership of a cooperative, and the practice of fishing and livestock farming. The table also examines household size, cultivated land area, proximity to a market, and household expenditure. These factors influence the adoption of improved maize seeds for sustainable intensification in rural areas of Cameroon. Clearly, rural households that adopt improved maize seeds are able to intensify maize cultivation by gaining better access to information, making increased use of external labour, expanding their arable land and investing in fertilisers and pesticides. Thus, with agricultural inputs held constant, households using improved maize seeds achieve higher yields than those that do not, suggesting that the adoption of improved seeds is intended to increase production. However, household size, the area of cultivated land, and proximity to a market are linked to a threshold effect that limits this impact.

The impact of adopting improved seeds on the intensification of maize production in rural Cameroon

The average impact of adopting improved seeds (ATT) is estimated using the nearest-neighbour matching method. The standard errors of these estimates are then calculated using bootstrapping with 100 replications.

Table 5. ATT of improved seeds on the intensification of maize production in rural areas of Cameroon

Group	Treatment	Comparison	Diff.	Std. error	t-stat
Unmatched	344.134	273.030	71.104	28.863	2.460
ATT	344.450	291.675	52.775	45.196	1.170
Bootstrap	100	100	100	100	100

Source: Author's calculations

On average, Table 5 shows that rural households that adopt improved maize seeds increase their yield by approximately 344.45 kg/ha, compared to 291.675 kg/ha for those that do not use them. Adopting improved maize seeds leads to higher yields: on average, households that adopt them produce 45.19 kg/ha more than those that do not. This positive ATT suggests that maize cultivation is being intensified through the use of improved seeds. This result is also observed in the unmatched group, albeit to a lesser extent. In this context, adopting improved seeds is essential for reducing labour costs and increasing profitability.

Following matching, no significant differences were observed in the means of the explanatory variables. Households that adopt improved

maize seeds and those that do not are comparable in terms of observable variables, making the comparison statistically valid.

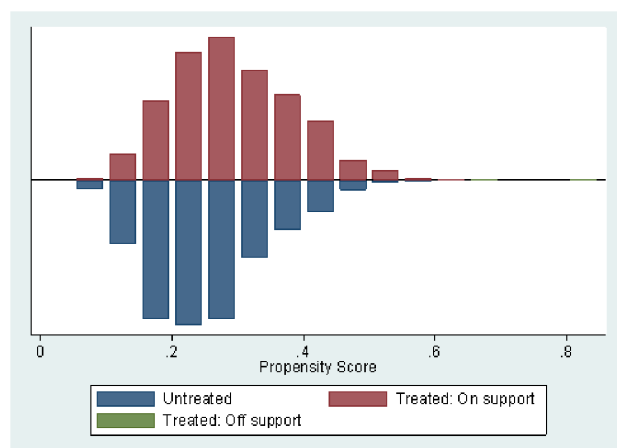


Figure 2. PSM distribution of improved maize seeds adoption in rural areas of Cameroon.

Similarly, when considered in conjunction with the distribution of propensity scores and common controls, the analysis shows that the distribution of propensity scores amongst maize-farming households is virtually zero, with an average overlap in probabilities between households that have adopted improved seeds and those that have not.

Estimation of the SFA production and cost functions for maize intensification

The results show that, at a 1% significance level, seed quantity, labour input and the quantity of inputs are significant independent variables in the stochastic production function.

Table 6. Maximum likelihood estimates of the parameters of the SFA production function

Boundary production function (normal/semi-normal)			
Variable	Production	ϕ_v^2	ϕ_u^2
Quantity of seeds	0.838*** (1.28e-05)		
Labour use	-0.447*** (7.16e-06)		
Quantity of inputs	-0.484*** (1.26e-05)		
Constant	5.197*** (5.16e-05)		
Observations	4101	4101	4101
Mean dependent variable	4.810		
Log likelihood	-8.7913455		
Prob > chi2	0.000		
SD dependent var	0.744		

Note: Error terms in brackets *** p<0.01, ** p<0.05, * p<0.1

Source: Author's calculations

According to Table 6, only the quantity of seeds exhibits a positive relationship with production, meaning that an increase in this variable results in an increase in production. In contrast, the coefficients for the labour-related variables and the quantity of inputs in the production function suggest that a one-unit change in these variables results in a 44.7% and 48.4% reduction in production, respectively. This can be explained by the law of diminishing returns, which states that increasing labour, fertilisers and pesticides boosts production up to a certain point, after which the effect becomes negative. Finally, the analysis shows that 74.4% of the gap between actual and potential

maize production is due to the technical inefficiency of crop intensification.

At the same time, analysis of the cost function (SFA) shows that the cost of factors such as seeds, labour, pesticides and fertilisers directly impacts the cost of intensifying maize production.

Table 7. Maximum likelihood estimates of the parameters of the stochastic frontier cost function

Boundary production function (normal/semi-normal)			
Variable	Total agricultural expenditure	ϕ_v^2	ϕ_u^2
Production	0.0538* (0.0327)		
Cost of seeds	38.80 (29.44)		
Labour expenses	0.0208 (0.0485)		
Expenditures on inputs	-38.67 (29.44)		
Constant	78.12 (52.79)	-0.691*** (0.0919)	-10.61 (176.8)
Observations	4094	4094	4094
Log likelihood	-254.443004		
Prob > chi2	0.000		
SD dependent var	0.744		

Note: Error terms in brackets *** p<0.01, ** p<0.05, * p<0.1

Source: Author's calculations

The constant term of -0.691 is significant at the 1% level because expenditure on fixed production factors, such as land and agricultural machinery, remains constant regardless of output. The positive coefficients for intensified production (0.05), the cost of seeds (38.8) and labour expenditure (0.02) indicate that an increase in the use of these factors will lead to a rise in total agricultural expenditure. However, since the coefficient for inputs is negative (-38.67), an increase in this variable whilst holding all other factors constant may reduce the household's total agricultural expenditure.

Thus, although adopting improved seeds can increase maize production, this remains inversely proportional to labour and resources. Consequently, production efficiency depends on a combination of rural households' internal resources and external inputs, such as seeds, fertiliser, and pesticides. Similarly, the intensification of maize production is negatively correlated with households' financial capacity, suggesting that better finances lead to more efficient production. An increase in the cost of seeds leads to a rise in the total cost of production. In contrast, a change in the cost of fertilisers and pesticides could result in a significant reduction, as households may choose not to use them when growing maize. Therefore, it is essential to ensure the timely availability of these additional resources and the labour required to utilise them (Tiffen & Mortimore, 1994).

However, the efficiency terms follow a truncated normal distribution because ϕ_u^2 is not statistically different from zero. This reflects the presence of inefficiency in maize production in rural areas of Cameroon. This inefficiency is primarily caused by factors outside the control of households, as the estimates of ϕ_v^2 and ϕ_u^2 are negative. This is likely due to environmental factors such as drought and flooding. The influence of random effects contributes to economic inefficiency, while increased external labour costs raise households' total agricultural expenditure.

Estimating the technical, allocative and economic efficiencies of intensifying maize cultivation among rural households in Cameroon

Table 8 shows that households in rural areas achieved technical, allocative, and economic efficiency rates of 52%, 81.5%, and 70.9%, respectively. This suggests that adopting improved maize seeds alongside other inputs is an effective production strategy. Conversely, the least efficient households require 31.2% more inputs to improve their efficiency, while the least economically efficient households need to make savings of 37.2% to become more efficient.

Table 8. Efficiencies of maize intensification in rural areas of Cameroon

Variable	Observations	Mean	t-stat	Min	Max
TE	4101	0.520	0.312	0.159	0.996
AE	4094	0.815	0.372	0.726	0.916
EE	4094	0.709	0.416	0.415	0.988

Source: Author's calculations

Although there is potential to improve the efficiency of rural households in the context of sustainable maize production intensification, the difference in average efficiency between households can only really be explained by the adoption of improved seeds, based on the average values for TE, AE and EE. Households that adopt improved maize seeds produce a higher yield with the same inputs as those that do not, and most of these households are efficient, achieving an average yield of 344.45 kg/ha. However, this yield is lower than the 530.35 kg/ha and 578.15 kg/ha reported by Takam Fongang et al. (2018). This suggests that households using improved maize seeds are more efficient and waste less in production than those that do not adopt them.

CONCLUSIONS

This study examined the theoretical, conceptual and empirical dimensions of the relationship between the adoption of improved maize seeds and sustainable agricultural intensification in rural areas of Cameroon. Overall, the analysis indicates that it is a complex and evolving relationship that necessitates various agricultural approaches tailored to existing systems to meet the needs of rural households. The main objective is to improve the efficiency with which other agricultural resources are used to enhance the overall efficiency of agricultural production. Therefore, the sustainability of agricultural intensification presents a technological challenge, and the adoption of improved seeds is considered an effective strategy for increasing agricultural production in a cost-effective and socially sustainable manner while mitigating the depletion of production resources. These seeds reduce pressure on production resources and improve rural household livelihoods, delivering economic, social and environmental benefits. They also improve the efficiency of agricultural production in rural areas by increasing yields and reducing input wastage. However, intensification through the use of fertilisers, pesticides and labour can hinder the adoption of improved seeds.

In Cameroon, rural households that choose to produce maize efficiently are influenced by the adoption of improved seeds, which promote sustainable, intensive production. However, the uptake of these seeds remains low due to inefficient supply chains, which hinders sustainable maize production. This situation is exacerbated by the degradation of natural resources and the pressures on rural households arising from their socio-demographic, economic, and institutional characteristics. These characteristics also encompass technological factors, such as the use of variable inputs and labour,

that are comparable to those involved in the sustainable intensification of agricultural production.

The findings of this study have significant implications for public policy and the economy. Consequently, any strategy aimed at promoting sustainable agricultural intensification for rural households in Cameroon should emphasise the systematic adoption of improved seeds, while also incorporating diversified farming systems, lower input prices, a favourable socio-economic environment, and support services for farmers. In particular, the supply of improved seeds should be increased, and markets and producer organisations should be supported to establish sustainable seed systems. These measures will promote efficient production, increase yields, and reduce losses among rural households.

However, while this study presents significant findings, it has methodological shortcomings, most notably a lack of data and indicators relating to environmental sustainability. The study was based on the 2017 CVFSA database, which focuses solely on maize yields associated with the use of improved seeds. Key ecological indicators, such as changes in land use and biodiversity, which are important for sustainable intensification, were omitted. Furthermore, the study is based on data from a single growing season, whereas environmental sustainability requires long-term monitoring. A more comprehensive analysis would enable the impact of improved maize seeds on natural resources to be assessed, while ensuring that increased agricultural yields do not harm ecosystems in rural Cameroon.

AUTHOR CONTRIBUTIONS

Conceptualisation: P.M. and P.N.; methodology: P.M.; data management: P.M.; formal analysis: P.M.; research: P.M. and P.N.; drafting of the first version: P.M.; supervision: P.N. All authors have read and approved the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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DATA AVAILABILITY

The 2017 Cameroon Food Survey and Vulnerability Analysis (CFSVA) is available and has been provided to the journal.

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