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GREEN TRANSITIONS

New perspectives on sustainability, innovation, resilient development and economic transformation

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Sustainability
Resilient pathways for future development

Green economy
Finance, policy and responsible growth

Innovation
Technology and optimization for change

JGEOR

Journal of Green Economy and Optimization Research

Vol. 1 • № 3 • October 2026

GREEN TRANSITIONS

Green Economy · Sustainable Development · Environmental Economics

ABOUT THIS ISSUE

October 2026 issue of the Journal of Green Economy and Optimization Research (JGEOR) brings together interdisciplinary research under the broad theme of "Green Transitions." The issue addresses contemporary challenges at the intersection of economy, ecology, water security and sustainable development, presenting studies that contribute to evidence-based policy, environmental management, resource efficiency, innovation and resilient development. The articles reflect JGEOR's commitment to publishing research that connects economic transformation with environmental responsibility and practical solutions for a more sustainable future.

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FOREWORD FROM THE EDITOR-IN-CHIEF

Green transitions

Dear readers,

Volume 1, No. 3 of the *Journal of Green Economy and Optimization Research (JGEOR)* is published under the broad theme of "Green Transitions", reflecting the growing need to align economic development with ecological resilience, resource security and long-term sustainability. The green transition is not a single-sector process. It requires simultaneous changes in energy systems, finance, production, consumption, land and water management, urban development, technology and public policy. Economic growth can no longer be considered independently from environmental limits, climate risks and the quality of natural resources on which societies depend. This issue brings together interdisciplinary research addressing the relationship between economy, ecology, water security and sustainable development. The studies presented examine different dimensions of environmental and economic transformation, including resource efficiency, sustainable management, environmental monitoring, green finance, innovation, ecosystem resilience and evidence-based decision-making.

"A successful green transition depends not only on new technologies, but on the quality of the decisions, institutions and investments that shape how natural and economic resources are managed."

A central principle of this issue is that sustainability should be understood as both an environmental and an economic objective. Degraded ecosystems, inefficient resource use, pollution and climate-related pressures can create direct economic costs through lower productivity, infrastructure damage, declining agricultural output, public-health burdens and increased vulnerability to environmental risks. Conversely, investment in cleaner technologies, ecosystem restoration, efficient resource management and environmental monitoring can strengthen both natural capital and economic resilience. The role of research is therefore fundamental. Reliable data, transparent methods and interdisciplinary analysis are needed to identify environmental pressures, measure their economic consequences and evaluate the effectiveness of proposed solutions. This is particularly important in regions undergoing rapid economic, urban and technological transformation, where environmental policy must respond to both development needs and ecological constraints. JGEOR continues to provide a platform for research that connects these dimensions. Our objective is to support studies that do not treat sustainability as an isolated concept, but rather examine how environmental responsibility can be incorporated into finance, governance, planning, innovation and economic decision-making. For JGEOR, **Green Transitions** represents a broader scientific and institutional direction: one in which development is evaluated not only by the scale of economic activity, but also by its efficiency, resilience and ability to preserve the natural systems on which future prosperity depends.

Ulvi Mammadov

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

Context sources

United Nations Environment Programme (UNEP). *Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication.* UNEP - UN Environment Programme

World Bank Group. *Natural Capital — Integrating Nature into Economic Planning and Sustainable Development.*

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Analysis of the relationship between digital banking and the development of cashless payments in Azerbaijan

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ABSTRACT

This study focuses on the interconnection between digital banking and cashless payments development in Azerbaijan on the basis of the official statistics and recent scientific works. The analysis is based on the Central Bank of the Republic of Azerbaijan digital payments reports (2023-2025), its official press-release (12 March 2026).. Descriptive statistics and year to year comparison are used, in addition content analysis. However, the cashless share of domestic card payments grew to 67.6% in 2025, and the value of domestic cashless card payments increased by 26% to AZN 99.1 billion. The value of current-account transfers made through digital banking was 82.5% of the current-account transfers by value, while the number of current-account transfers made through digital banking was 94.4% of the current-account transfers by number. In 2019, internet-banking transfers have totalled AZN 308.9 billion, mobile-banking transfers – AZN 73 billion. Increase in the number of Instant Payments System transactions by 12.5 times and implementation of the unified AZQR standard enhanced account-based payments. The results show that digital banking correlates with cashless transformation, which is due to convenience, reduction of transaction cost, high level of acceptance infrastructure, increased competition, and user trust (the descriptive design does not imply causal effect). However, cyber security, digital literacy, unequal access and data protection are still relevant limitations.

INTRODUCTION

The accelerated digitalization of financial services has revolutionized the nature of contemporary banking, allowing people, companies, and public institutions to access, move and handle money differently. Digital banking refers to a wide variety of channels for providing financial services remotely, such as mobile banking apps, Internet banking, electronic money, instant payment systems, QR-based payments and any other technology-enabled platforms. These channels can lower transaction costs, enhance service accessibility, speed up payment processing and increase the traceability of financial flows, by decreasing reliance on physical branches and cash-based transactions. Simultaneously, they require users to believe that the technology is useful and reliable, that they have the digital skills needed to use it, and that the payment ecosystem is secure, to adopt them effectively (Jain & Jain, 2025). Digital banking therefore shouldn't be viewed as a technology innovation in the commercial banking sector but also as an institutional part of a greater movement towards a cashless and increasingly data-driven economy.

In many emerging and transition economies, governments and regulators are interested in expanding cashless payments as a policy goal and are interested in reducing frictions in transactions, expanding financial inclusion, enhancing transparency, and formalizing economic activity. Another potential benefit of digital payments is that they can help to better track financial transactions, as electronic payments provide more structured and traceable data than cash transactions. This dimension plays a special role in the financial management of public-sector and organizations. The modern study of the process of digitalisation of financial control in budget organisations in Azerbaijan shows that in the modern world, the role of financial control in budget organisations is widely increasing in connection with the use of technology and the entire socio-economic process of development of the country (Sadiqov & Latifova, 2026). Likewise, research on enterprise-level digital transformation highlights the growing importance of digital management systems, enterprise resource planning (ERP) software, financial tools, and the electronic exchange of documents, which are reshaping organizational operations and financial management (Rahimli, 2026). The developments show that digital banking is much more than that and exists in a wider digital banking environment where payments, accounting, controlling, reporting and management systems are increasingly interwoven.

The human-capital side to this shift is also significant. Digital technology can be utilized to improve the business performance of firms, financial institutions and public organizations, but this requires the skills and professional competencies of employees and users, among others. An analysis of professional accounting education and International Financial Reporting Standards adoption by Samadova and Gasimov (2026) highlights the link between contemporary professional competencies, employability and financial-reporting transparency. Their study is not specifically on digital payments but it is relevant to the current research as digitalization of banking and payment systems significantly demand employees and users to be able to work in transparent and technology-rich financial spaces. The general issue of enhancing the green and digital competencies of young people has also been recognized as one of the key components of Azerbaijan's shift towards a knowledge-based and sustainable economy (Guluzade, 2026). These are indicators that technological infrastructure is not sufficient to ensure a successful digital transformation, financial literacy, digital competence and institutional capacity are also required.

The financial digitalization and sustainable economic development has an additional dimension to the analysis. An increasingly important role for financial systems is to allocate resources in a way that allows for environmentally and socially sustainable activities, and not just efficient payments. For instance, Mammadov (2025) assesses the knowledge and perceptions of green finance among youth in Azerbaijan, reflecting the increasing significance of new financial concepts in the public consciousness and financial decision-making processes. Meanwhile, a number of studies in various fields show that Azerbaijan's overall economic-development program is more and more focusing on the combination of technological modernization and environmental factors. Research on the changes in water level in the Caspian Sea and in strategic inland water systems highlights the need for data-driven assessments for economic and environmental decision-making (Qadimli et al., 2026), and urban studies in Baku show that the development and built-up density of cities are spatially intensive and can affect environmental conditions like land surface temperature (Qadimli, Arifzade, Mammadov, & Gadimli, 2026). While these studies are different methodologically from the study of digital banking, they are all examples of a new policy landscape, one that increasingly relies on digital data, monitoring systems and quantitative indicators to inform economic decisions.

Similar data across other industries further highlight the importance of integrated digital and sustainable-development approaches. In the analysis of urban expansion, vegetation patterns and surface heat distribution in Luanda, Qadimli and Mammadov (2026) show the importance of data-based assessment to understand the impacts of rapid structural change. Turning to tourism, Zeynalova and Asgarova (2026) analyze the state of readiness of a riverfront tourist destination in Mingachevir, and the rising significance of sustainability indicators in a local economic-development plan. While these studies do not directly concern banking, they do speak to environmental and tourism issues and supply a general analytical framework for the current study: modern economic transformation involves more and more measurable indicators, digital information systems and evidence-based decision-making. The statistics of digital banking and cashless-payments are an example of this transition in the financial sector.

The evolution of digital banking in Azerbaijan has gained momentum in parallel with the reforms in the national payment system and regulation. The Central Bank of the Republic of Azerbaijan has recognized the increase in digital payments and decreasing dependence on cash as one of the significant aspects of development of financial sector. In recent years, the regulatory framework for digital financial services has been improved due to the introduction of new legislation on payment services, the regulation of interchange fees, the development of instant-payment infrastructure and the implementation of the Financial Sector Development Strategy (2024-2026) (Central Bank of the Republic of Azerbaijan [CBAR], 2024). Mobile and internet banking has been gradually gaining significance in the area of current-account transfers, and payment cards are increasingly used for direct cashless purchases instead of mainly cash withdrawal. The technological grounds for account-to-account and QR payments have further grown with the development of the Instant Payments System and the launch of unified AZQR standard.

However, an increase in digital-payment volumes does not necessarily translate into a cashless economy and the equal distribution of it throughout the population. The level of use of digital financial services may vary among different population groups, driven by variations in income, age, education, geographic location, access to digital devices, and financial literacy. Globally, digital connectivity and mobile-phone ownership have been shown to have a strong relationship with participation in financial services, and gaps in access and capability can hinder digital transformation's inclusiveness (Klapper et al., 2025). Further challenges are security risks. Phishing, social engineering, unauthorized access, data breaches and other types of digital fraud can make consumers less interested and less confident in adopting digital channels. Consumer protection, cybersecurity, operational resilience, clear and transparent payment costs and systems to resolve payment disputes are also crucial to the continued growth of cashless payments.

Although there is an increasing amount of international publications on digital payments, financial inclusion and technology adoption, the Azerbaijani context of digital-banking channel expansion and cashless payments is still poorly explored using the latest official data. Often, the papers focus on a single country or type of adoption behaviour, or on financial inclusion and the overall benefits and risks of digital payments. The co-evolution of payment-card activity, mobile and internet banking, current-account transfers, instant payments and QR in Azerbaijan's current institutional environment has received comparatively less attention. This gap is especially pertinent in light of recent developments in the national payment system that offer a chance to evaluate the extent to which various measures of the advancement of digital banking and cashless-payment align.

Based on this, the aim of this study is to analyze the link between digital banking and development of cashless payments in Azerbaijan based on official data of the Central Bank and the latest scientific publications. The analysis covers shifts in the value and share of cashless payments made through domestic cashless payment cards, digital current-account transfers, shares of internet- and mobile-banking activity, the growth of the Instant Payments System, QR-based cashless payments, and cashless-payment usage differences among selected cardholder groups. The study does not attempt to draw causal conclusions for the co-movement of all these indicators, but rather to describe the institutional and technological mechanisms that may have contributed to this co-movement. It aims in this way to give a new evaluation of Azerbaijan's transition to more digital, transparent, inclusive and cashless financial system and to pinpoint key policy and research challenges that have yet to be addressed.

LITERATURE REVIEW

Digital banking and cashless payments have been a recent phenomenon in the banking sector, with financial institutions, governments, and consumers all embracing mobile banking, internet banking, instant-payment systems, digital wallets, and QR-based payment technologies, giving rise to a body of literature. Much of this literature is on behavioural determinants of digital financial service adoption. According to Jain and Jain (2025), systematic review of adoption of digital payments showed that convenience, perceived usefulness, trust and ease of use are the primary factors that motivate consumers to adopt digital payments over traditional cash-based payments. Meanwhile, the fear of security issues, privacy issues, lack of technology knowledge and lack of confidence in dispute resolution can be barriers to adoption. Mezoh and Zhou (2024) also link cashless-payment systems to lower transaction costs, increased efficiency and clearer transparency, stressing that a lack of infrastructure and consumer confidence could limit their impact, especially in developing economies.

The other significant theme of literature is that digital payments are a tool for financial inclusion. Shahen and Sharaf (2025) state that digital-payment technologies have the potential to reach out formal financial services to people who have traditionally been hard to reach in terms of traditional financial services. Digital platforms can potentially lower geographical and transactional barriers, especially if financial services are available via mobile devices without frequent trips to a bank branch. Interoperability between digital-payment platforms is another important aspect, as Alok et al. (2024) show that the availability of the payment infrastructure across platforms is linked to the access to formal financial markets. Digital connectivity also plays a key role in modern financial inclusion, and the Global Findex Database 2025 demonstrates that mobile-phone ownership, internet access, and digital account availability have a growing impact on formal financial system participation (Klapper et al., 2025). The same literature, however, shows that inequalities of income, age, education, location and digital capabilities still play an important role as barriers.

Digital transformation in the financial sector must also be taken into account within the general framework of digitalization of organisations and economic institutions. Rahimli (2026) discusses enterprise digital transformation, such as digital management systems, enterprise resource planning systems, financial software, and electronic document circulation, emphasizing the transition from paper-based to digital management systems. This is applicable to digital banking, as payment systems are now more deeply integrated into accounting, enterprise-resource-planning, reporting and treasury-management systems. Likewise, Sadiqov and Latifova (2026) study the digitalization of financial control in budget organizations and socio-economic development indicators. They expand the debate on private banking to show that digital financial technologies are equally emerging as significant tools of public-sector control, monitoring and financial administration.

A second key part of the digital transformation lexicon is financial transparency. Samadova and Gasimov (2026) explore the linkages among professionally-oriented accounting education, adoption of International Financial Reporting Standards, employability of accounting graduates, and financial-reporting transparency. Their study is not directly related to an analysis of electronic payments, but it is to the institutional context in which electronic banking takes place. In today's digital era, payments, accounting and reporting are increasingly becoming digital, which means that financial professionals need to be able to work in technologically integrated and transparent information systems. Thus, the success of financial digitalization is not limited to infrastructure and software but also on human resources, professional skills, and institutional capabilities.

The significance of skills and financial literacy is also evident in the research on Azerbaijan's overall transition to digital and sustainable economy. Guluzade (2026) highlights the importance of education and the development of green-skills for young people to enhance green-economy knowledge in Azerbaijan. Mammadov (2025) addresses specifically the issue of green finance, and explores the knowledge and perceptions of the youth on green-finance concepts in the Azerbaijani context. These studies suggest that awareness, education and skill set can play a role in determining how an individual can effectively participate in the emerging financial and economic systems. This applies to banking too: having access to a mobile device or a bank account does not always mean that a user is able to use mobile banking, electronic payments, QR systems or other digital-finance tools to their benefit if they are not sufficiently digitally and financially literate.

Comparative information from other transition economies offers further context. Bibi and Yerzhan (2025) examine how digital-payment instruments and the development of central-bank digital currency (CBDC) have unfolded in Kazakhstan; they note how technological progress, private digital payment systems, public trust, and governance have all interacted in the development of digital payment instruments in Kazakhstan. Kakhniashvili (2024) discusses the process of digitalization of the banking system in Georgia and highlights the disparities in institutional development and persistent regulatory issues. According to G'aniyev (2025), digital payments in Uzbekistan have grown significantly, but there are still gaps regarding access based on socio-economic and regional factors. The studies indicate that technological readiness is not enough to ensure broad-based digital-payment adoption. The reality of the penetration of digital banking services is impacted by institutional quality, consumer confidence, financial literacy, regulation, competition and equitable access.

In the literature about Azerbaijan, there is growing evidence of a broadening shift to data-based economic and policy analysis. For instance, Qadimli et al. (2026) analyze the variability of water levels and economic vulnerability of the Caspian Sea and the key inland water bodies. In another study, Qadimli et al. 2026 evaluate the urbanization, built-up density, and land surface temperature correlation in the central part of Baku city. Qadimli and Mammadov (2026) also study urban expansion, vegetation distribution and surface heat fluxes in Luanda. These studies focus on the environment and not on financial processes, but the methodological approach is a hallmark of the growing trend and central practice of economics research today: institutional and policy decisions are more and more made based on measurable digital indicators or quantitative monitoring systems. The digital-payment statistics thus reflect this more general data-driven shift in the financial sector.

Another piece of research that focuses on sustainability also shows the growing intersection between digital and financial modernization, and sectoral development. As in the case of green-tourism readiness assessment in Mingachevir by Zeynalova and Asgarova (2026), sustainability indicators are becoming more important in local development planning. This literature, along with green skills and green finance studies, studies on green urban environmental change, and studies on economic exposure, shows that Azerbaijan's development agenda is becoming more closely aligned with measurable sustainability, technological modernization and evidence-based decision making (Guluzade, 2026; Mammadov, 2025; Qadimli et al., 2026; Zeynalova & Asgarova, 2026). These studies don't necessarily measure the degree of digital-payment adoption, but they do offer valuable context of the broader shift to more transparent, data-driven and tech-focused economic systems in which cashless transactions can be understood.

Although there are a considerable number of international and regional studies on the topic, there is a significant empirical lack in the study of the recent development of digital banking and cashless payments, particularly in Azerbaijan. Much of the literature reviewed has focused on consumer adoption, financial inclusion, institutional digitalization or individual technologies. Regional studies are helpful but fail to reflect the unique regulatory context, payment system and recent transaction trends in Azerbaijan. Moreover, there is relatively little research which compares payment-card turnover, internet banking, mobile banking, digital current-account transfers, instant-payment activity, QR transactions, and payment-card users' segmentation in the same national context. The swift dynamics observed by the Central Bank of the Republic of Azerbaijan in 2023-2025 thus offer an occasion to expand the literature with an all-encompassing assessment of Azerbaijan's digital-payment landscape.

Therefore, the present study adds to the literature and uses recent official indicators of the Central Bank, literature from international, regional and Azerbaijan-specific studies. The analysis does not only focus on technology adoption or financial inclusion, but also on the development of various different digital channels at the same time, and how the recent evolution of these channels is compatible with a wider trend towards cashless financial activity. Meanwhile, the research does not imply causality, but rather an association: an increase in digital banking and cashless payments could be driven by regulatory reforms, investments in infrastructure, consumer habits, competition, and the broader economic digitalization. This distinction gives the conceptual underpinning for the descriptive, empirical approach taken in the sections that follow.

MATERIALS AND METHODS

Research design

The research design of this study is quantitative descriptive and the secondary data research that aims at investigating the connection between the expansion of digital banking channels and development of cashless payments in Azerbaijan. The methodological approach includes descriptive statistical analysis, year-to-year comparison, indicator-based trend assessment and qualitative content analysis of official regulatory and policy documents. The study is not designed to econometrically estimate a causal model; therefore, the associations and co-movements between the digital-banking indicators and level of cashless payment observed in the study are not necessarily interpreted as direct evidence of causation. This method is aligned with the aim of revealing the latest trends in Azerbaijan's payment system, relying on the latest available national statistics.

Data sources

Official publications of the Central Bank of the Republic of Azerbaijan (CBAR) have been used as the main source of empirical information. The data spans the years 2023–2025 and is mainly based on the Digital Payments Reports for 2023, 2024 and 2025, as well as the CBAR press release issued on 12 March 2026 on the ongoing growth of digital payments (CBAR, 2024, 2025, 2026a, 2026b). These sources were chosen because they set out nationally aggregated indicators in the areas of card payments, current-account transfers, Internet and mobile banking, Instant Payments System, and QR-Based Transactions. Official CBAR statistics also makes it possible to ensure consistency with the regulatory definitions and reporting system used in Azerbaijan's financial system.

The trends were interpreted and set in the context of a broader theoretical and regional framework using secondary academic literature. The literature spans the uptake of digital payments, financial inclusion, institutional digitalisation, professional skills, financial transparency and broader digitalisation of the economy. However, academic studies were not used to replace or reconstruct official payment statistics; quantitative results in the empirical section are mostly based on data from CBAR.

Indicator selection

Analysis is carried out on the basis of six major categories of indicators. The indicators were chosen because collectively they reflect the value, volume, intensity, cashless-payment channel composition and inclusiveness of cashless-payment activity in Azerbaijan:

1. Domestic cashless card payments, defined as the total amount of cashless card payments and the share of these payments in the total amount of domestic card payments;
2. Digital current-account transfers (in number and value);
3. The value of internet-banking and mobile-banking transfers, as well as the annual growth rate of these reported values;
4. Activity on the Instant Payments System, such as number of transactions and value of transactions;
5. QR-based payment activity and QR development by AZQR, which has been reported as an increase in QR transactions via Instant Payments System; and
6. Compares cashless-payment shares by cardholder type, including salary cards and social cards, the latter of which is used as a proxy for the difference in adoption by cardholder types.

These indicators are thus representative of bank-card based and account based payment channels. The importance of this is that the rise of a cashless economy cannot be measured by card-payment values alone; internet banking, mobile banking, instant transfers and QR-based payments are now an increasing part of the national digital-payment system, but are also distinct and stand on their own.

Data processing and calculations are not necessary

Values were first organised year-wise and by payment channel as officially reported. Absolute changes, percentage and percentage-point changes were then calculated to determine direction and size of developments between reporting periods. For those items where the current year value and the official YOY growth rate were available and previous year value was not directly reported, previous year value was reverse-calculated.

The following formula was used:

$$V_{t-1} = \frac{Vt}{1+g}$$

where:

V_t represents the reported value in the current year;

V_{t-1} represents the estimated value for the previous year; and

g represents the reported year-on-year growth rate expressed as a decimal.

For instance, the internet-banking transfer volumes in 2025 amounted to AZN 308.9 billion and grew by 12.4% compared to the previous year. The same value for 2024 was thus calculated as:

$$\frac{308.9}{1.124} \approx 274.8\ billion\ AZN$$

Only where the official source provided a growth rate in addition to a value was the same procedure used. The calculated values are considered derived estimates and are so indicated in the appropriate discussion and figure notes. This distinction is required to keep the difference between reported statistics and calculations by the author transparent.

Analytical approach

The empirical analysis takes place in 4 stages, each of which represents one of the key elements of Azerbaijan's digital-payment transformation. First, alterations in the volume and share of in-country cashless card transactions are analysed to assess the shift from cash withdrawal to direct electronic transactions. Secondly, statistical analyses of internet/mobile banking show how remote channels are becoming more and more relevant to current-account transfers. Third, the activity in the Instant Payments System and in QR-payments is assessed as a measure of the progress towards an interoperable account-based payment infrastructure. Fourth, the split between salary-card and social-card cashless-payment shares is examined to see if there is any discrepancy in cashless-payment adoption.

The focus of the interpretation is on the co-movement of these indicators. The simultaneous growth of cashless card turnover, digital transfers, internet and mobile banking, and instant payments and QR transactions is seen as proof of a digital-payment revolution. However, this simultaneous expansion is not enough in itself to prove that the rise in cashless-payment transactions is solely due to digital banking. Wider economic digitalization, merchant acceptance infrastructure, competition between banks and payment institutions, household income and inflation and regulatory change may also affect the observed changes.

Content analysis

Qualitative content analysis was also used with pertinent documents from CBAR publications and policy documents in the numerical comparison analysis. Special focus was placed on institutional developments in the field of payment-services regulation, the Financial Sector Development Strategy for 2024–2026, the regulation of interchange fees, the Instant Payments System, and the creation of a unified AZQR standard. The statistical results are interpreted in view of these institutional factors and mechanisms of how regulatory and technology changes can promote the adoption of cashless payments are identified.

A comparative analysis of academic literature was also conducted to determine Azerbaijan specific developments from general international and regional developments. The studies related to Kazakhstan, Georgia and Uzbekistan are not presented as statistically comparable data; rather, they are used as contextual benchmarks as they provide different indicators, over different time periods, with different institutional frameworks, and using different methodologies than the CBAR data.

Methodological limitations

The results should be interpreted with some limitations in mind. First, the analysis is based on aggregate national statistics – no microdata on transactions, households, merchants, or banks are used. This makes it impossible to systematically distinguish the digital-payment behaviour of different age groups, income groups, levels of education, professions, regions and individual financial institutions. The comparison of the salary-card and social-card is just one measure of user-group heterogeneity.

Secondly, the main observation period 2023–2025 is comparatively short. While indicators of change are available that indicate significant change, the time series would need to be longer to help differentiate between a short-term fluctuation and a more enduring structural change. Increases or decreases in nominal transaction value should not be unwarrantedly assumed to be increases or decreases in real payment activity as it can also be a result of inflation or an increase or decrease in consumer spending in general.

Third, some values for previous years are computed from values in the current year and growth rates rather than being directly reported in tables. The calculation method is mathematically clear, but the values thus obtained are to be regarded as estimates.

Lastly, descriptive analysis has been used in this study, therefore, there is no causal effect shown on the impact of digital banking on cashless-payment development. Longer panel data, ideally broken down by region, bank, age group and income category and merchant type and payment channel would be needed to perform a more stringent causal analysis, along with the correct explanatory and control variables. Depending on the availability of detailed data, future research could therefore expand upon the current analysis by using either panels or time-series or microeconometric approaches.

RESULTS AND DISCUSSION

Payment transformation towards cashless transaction in cards

The single most visible sign of Azerbaijan's progress in the migration to cashless economy is the growth in value and share of domestic cashless card payments. The Central Bank of the Republic of Azerbaijan reports that cashless card payments in the country totaled AZN 99.1 billion in 2025, 26% more than the previous year. Meanwhile the cashless component of domestic card turnover increased 3.4 percentage points to 67.6%. The findings suggest that payment cards are increasingly used for direct retail purchases and electronic settlements and not just as tools to use when withdrawing cash.

Based on the officially reported growth rate, the estimated amount of domestic cashless card payments in 2024 is about AZN 78.7 billion. This means that the increase will be approximately AZN 20.4 billion per year. This change is significant and aligns with the overall growth of digital payment platforms, merchant acceptance, mobile banking apps, and consumer awareness of digital payments. However, nominal growth needs to be viewed with caution as some of the growth can be due to the general price inflation and expansion in overall consumer expenditure and not necessarily due to an equivalent growth in the number of goods and services that are being bought using cashless methods.

The increase in cashless share is especially significant since it is a structural measure, less subject to fluctuations in nominal prices than transaction value alone. The growing proportion of overall card turnover that is now realized in non-cash offers evidence for a behavioral change in cardholders' consumption of banking products. This aligns with the results of Jain and Jain (2025) which reveals that convenience, perceived usefulness and trust are critical factors for the adoption of digital-payment. The higher availability of point-of-sale terminals, online commerce, mobile applications, QR-based payment and instant transfer services may all contribute to strengthening this change in Azerbaijan.

The observed trend is also relevant for the transparency of financial statements. Payment by electronic means generates traceable payment records and can be used to better monitor financial transactions than cash based transactions. This wider transparency aspect is aligned with research that highlights the role of digital systems with financial control and reporting. Sadiqov and Latifova (2026), for instance, link the digitalization of financial control with the enhancement of organizational monitoring, while Samadova and Gasimov (2026) highlight the need for modern financial competences and reporting standards for strengthening transparency. All of these studies are related to different institutional contexts, but they further support the overall claim that digitalization can lead to better quality and traceability of financial information.

Table 1. Key indicators, 2025

Indicator	Value
Cashless card payment value	AZN 99.1 bn
Cashless share of card turnover	67.6%
Digital transfer share by number	94.4%
Digital transfer share by value	82.5%
Internet-banking transfers	AZN 308.9 bn
Mobile-banking transfers	AZN 73 bn

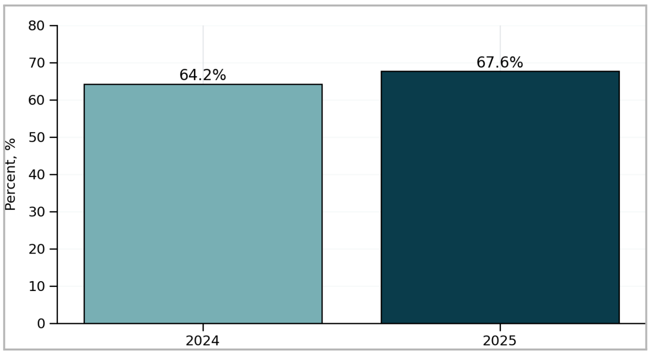

Figure 1. Cashless share of domestic card turnover, 2024-2025
Source: Prepared by the author using CBAR (2026a). Calculated values are disclosed in the relevant figure note.

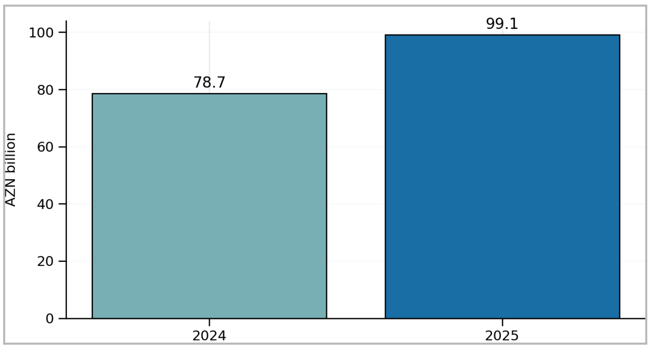

Figure 2. Value of domestic cashless card payments, 2024-2025
Source: Prepared by the author using CBAR (2026a). Calculated values are disclosed in the relevant figure note.

The simultaneous growth of the cashless-payment value and the cashless share thus offers more evidence of structural change than using either indicator alone. The descriptive nature of this analysis, however, makes it impossible to quantify the extent to which this change is due to digital banking alone, or due to regulation, merchant acceptance, growth in household income, inflation, and a variety of macro-economic factors.

Mobile and Internet banking are available.

Digital banking is now the main channel for current-account transfers in Azerbaijan. Digital channels were responsible for 94.4% of current-account transfers in 2025, measured by number and 82.5% by value. The transfer via the internet banking grew by 12.4% up to AZN 308.9 billion and via the mobile banking grew by 14.3% up to AZN 73 billion. These numbers show that the use of remote banking channels is no longer a secondary way to perform a large portion of account-based transfers but rather the primary way to perform those transfers.

The distinction between the share by number and the share by value is important from an analytical perspective. The number of transactions done on digital channels is significantly higher relative to the number of transactions done on non-digital channels, which indicates that digital channels have a stronger share for more frequent day-to-day transactions. However, Internet banking shows a much bigger total value than mobile banking, again reflecting a higher contribution to higher value corporate/business/treasury/institutional transfers. This should be interpreted with caution as available CBAR statistics do not directly present a distribution by transaction size. This limitation is already addressed in the current manuscript.

The growth of internet and mobile banking is also aligned with the overall digitalization of enterprises. In his article, Rahimli (2026) was highlighting the growing significance of Enterprise Resource Planning (ERP) systems, financial software, and electronic document circulation in enterprise management. Such systems are likely to become more common, and banking transactions could be embedded more and more into accounting, treasury, procurement, and reporting processes. Digital banking can, therefore, not only help increase convenience in everyday life, but also automate business-related financial processes.

The professional competence and institutional readiness are also crucial to the digitalization of financial services. In the context of today's financial education, Samadova and Gasimov (2026) emphasize the connection between professionalism, employability, and transparency in reporting. Accountants, finance professionals, managers and banking staff must possess the skills needed to operate integrated digital platforms, in a highly digital financial landscape. This means that the rollout of cashless payments is a mix of technological and human-capital processes.

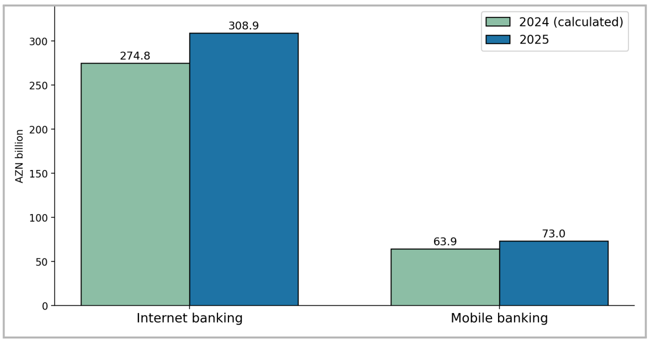

Figure 3. Internet- and mobile-banking transfers
Source: Prepared by the author using CBAR (2026a). Calculated values are disclosed in the relevant figure note.

The results thus suggest the possibility of a shift towards a predominantly digital banking system, at least for routine transfers, in Azerbaijan. But, this doesn't necessarily mean that branch-based services are no longer important in a fully digital system. Physical banking infrastructure could still be relevant for more complicated financial products, providing customer support, financial advice, identity verification, and riskier transactions. A hybrid approach, where regular transactions go online whilst the branches deal with high-touch, high-ticket and high value-added transactions, may therefore be more realistic than the complete branch replacement approach.

Instant payments & AZQR

The development of the Instant Payments System is one of the most significant implications of structural change of Azerbaijan's payment system. The number of Instant Payments System transactions grew 12.5 times in 2025, compared to 2024, with the value of transactions growing 90.1%. Furthermore, the number and value of QR payments made via the system grew by 6.2 times and 7.1 times, respectively, in the second half of 2025 compared to the first half of the year. These growth rates indicate that the account-to-account payment solutions are starting to be used alongside the traditional card-based payment solutions.

Interoperability can minimise fragmentation between banks and payment providers, making the development of the unified AZQR standard particularly important. A uniform QR system could help to reduce the acceptance fees for small businesses, ease payment on customer end, and help to make account-based payments more accessible and available without needing a traditional card terminal infrastructure. This may apply especially to micro and small businesses where the cost of adopting and running traditional point-of-sale hardware may be relatively high.

Interoperability is also a key element in the literature. Alok et al. (2024) find a correlation between the development of cross-platform digital-payment infrastructure and increased financial access and tighter connections to formal credit markets. Therefore, it is possible to consider Azerbaijan's AZQR project not only as a technological invention, but also as a component of a large infrastructure project, which can help to achieve financial inclusion, competition and lower payment costs.

The regional trends are also in the same direction. The current manuscript also mentions that Uzbekistan has made strides towards adopting a universal QR system, suggesting that the development of standardized QR payments is a growing trend in the region. This convergence could be an opportunity for increased digital-payment interoperability and harmonisation of digital-payment standards in the longer term across neighbouring transition economies.

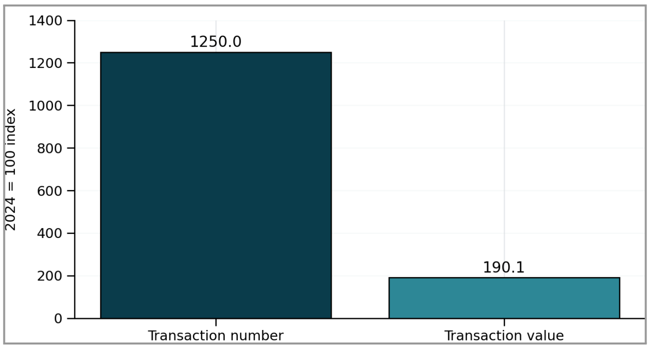

Figure 4. Growth indices for the Instant Payments System Source: Prepared by the author using CBAR (2026a). Calculated values are disclosed in the relevant figure note.

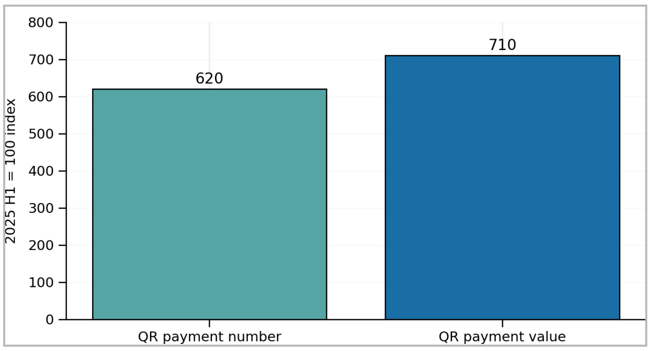

Figure 5. Growth indices for QR payments through the system Source: Prepared by the author using CBAR (2026a). Calculated values are disclosed in the relevant figure note.

While QR and instant payments are growing, sustainability goes beyond transactions. A reliable system uptime, instant confirmation of transactions, straightforward refund process, robust cybersecurity measures, affordable fees, and clear responsibility in case of payment conflicts are all critical factors that need to be addressed. Consumer protection is thus an inherent part of infrastructure development.

The growth from a fairly low level base must also be viewed with careful optimism. The 12.5 times rise in the number of transactions is statistically significant but not necessarily indicative of transactions at the same absolute volume on the Instant Payments System as for card payments or traditional account transfers. The focus of future research should therefore be on absolute volume of transactions and penetration of users, and not only on growth indices.

Financial inclusion and digital skills and unequal adoption

Growth in the number of digital payments has not been even among all customer segments. However, the share for cashless-payments was 54.2% for salary cards and 20% for social cards. The cashless share of social cards rose 9 percentage points in three years, but there is still a significant gap to be made up. This indicates that constructing a payment system does not necessarily result in equitable uptake across all segments of society.

There can be a number of reasons for this difference. Digital illiteracy, low-income families, rural populations, and older users may not be as likely to engage with mobile banking, QR payments or other electronic means. Behaviour may also be determined by device ownership, internet connectivity, familiarity with applications, fear of fraud and preference for cash. These findings are largely in line with the Global Findex literature, which highlights income, age, location and digital connectivity as key drivers of financial-service participation.

This is particularly significant in the human-capital aspect. Guluzade (2026) highlights the importance of education and skills development for Azerbaijan's shift towards a green and knowledge-based economy. While the study deals with green skills, the same holds true for digital finance: the availability of infrastructure needs to be combined with the capacity to make effective use of it. Likewise, Mammadov (2025) shows that even among the younger population groups, one cannot take for granted the common understanding and perception of green finance. Financial and digital-literacy programs are thus needed to ensure digital-payment inclusion, in addition to infrastructure development.

Digital inclusion should be understood in a broader development context, as well. Increasingly, recent studies of Azerbaijan rely on digital indicators and/or technical processing of the indicators to evaluate economic and environmental change. For example, Qadimli et al. (2026) assess water-level variability and economic exposure using data from satellites, and Qadimli et al. (2026) analyze urbanization and land surface temperature in the central part of Baku. Qadimli and Mammadov (2026) also study the urban extension, vegetation distribution, and thermal surface distribution in Luanda. While these studies do not represent banking, they do signify a similar shift to data-driven decision making and digital monitoring, and one that is occurring across the entire industry.

The use of digital payments in a more inclusive way may also contribute to other areas of economic development. Zeynalova and Asgarova (2026) gauge the stage of preparation of green-tourism in Mingachevir, where the expansion of services for tourists and the local economy can be increasingly based on the acceptance of electronic payments. In such cases, cashless infrastructure can have an impact on improving the ability of small businesses to cater to both local and export markets, which needs sectoral empirical studies.

Risks of cybersecurity, trust and institutions

The digital banking trend also puts more banks at risk from cyber and operational threats. Direct financial losses and decreased consumer confidence may result from phishing, social engineering, account takeover, fraudulent payment links, unauthorized transactions, malicious applications, and data breaches. Trust, therefore, isn't a secondary factor, but a key driver of the sustainability of cashless-payment growth.

Payment institutions and banks should adopt robust authentication, behavioural transaction monitoring, real-time alerts, fraud-detection systems, transaction limits, device verification, and quick dispute-resolution processes. But technology security measures are not enough. Users also need to be able to identify fake communications and know a few principles of cyber-hygiene.

Thus, there is a two-sided relationship between digitalization and transparency. While digital platforms can enhance financial traceability and institutional control, as Sadiqov and Latifova (2026) argue, they can also introduce new risks and vulnerabilities if cybersecurity governance is not keeping pace with adoption. Hence, the success of Azerbaijan's cashless transformation cannot be only measured by transaction growth, but by the level of fraud, the resilience of the system, the speed of complaint processing and consumer confidence.

The overall assessment of the digital banking–cashless payment relationship

In combination, the findings provide a uniform picture on several indicators. Cashless value and share of card payments rose, digital channels for current-account transfers accounted for the vast majority of transactions, Instant Payments System activity grew significantly and QR payments had especially strong growth. All these indicators are moving in the same direction, thus confirming the link that digital banking is closely related to the development of cashless payments in Azerbaijan.

However, this should not be understood as just a one-way causal mechanism. Technological investment, regulation of payment services, merchant infrastructure, financial institutions rivalry, consumer behaviour, income growth, digital literacy, cyber security and overall economic digitalization will probably be key factors driving the transformation. It is not possible to detect these effects econometrically in the current aggregate data.

The main novelty of the current analysis lies in the fact that shows Azerbaijan's recent cashless transformation does not limit to one payment instrument. It is the simultaneous growth of card payments, account-based transfers, mobile and internet banking, instant payments and QR based infrastructure. The development across multiple channels is a good indication of a structural digital transformation rather than growth by one particular payment channel.

Meanwhile, the salary-card and social-card analysis shows that the gains of this change are not equal. Future policy should thus look at both scale and inclusion; scale in terms of volume of digital transactions, and inclusion of older people, lower income people, rural people and those not so tech-savvy from the emerging cashless financial system.

CONCLUSIONS

The study shows that Azerbaijan has seen a clear expansion of the digital banking and cashless payments in 2023-2025 through multiple channels. The most compelling evidence is that all of these new domestic cashless card payments, internet and mobile banking, digital current-account transfers, the Instant Payments System and QR-based transactions have been growing at the same time. Domestic cashless card payments totaled AZN 99.1 billion in 2025, and the share of domestic cashless card services in the total domestic card payments was 67.6%. 94.4% of current-account transfers took place via digital channels, both by number and by value, indicating that digital channels have become a key pillar of the national payment system.

The fast development of the Instant Payments System and QR-based payments are also an sign that the transformation of Azerbaijan towards a cashless society goes beyond the traditional card system towards interoperable and account-based payments. Growth in the number of Instant Payments System transactions, as well as expansion of AZQR, indicates that consumers and businesses are increasingly seeing lower cost and more flexible payments systems as a key priority. But there's also evidence from the data that adoption is not even. This strong gap in cashless-payment usage between social-card and salary-card holders suggests a persistent gap in several areas: digital capability, income, age, access and user confidence.

The results should however be analyzed in the light of the limitations of the research design. The study is descriptive, using aggregate official statistics and thus does not allow drawing a causal effect of digital banking on the growth of cashless payments. Regulatory reform, merchant infrastructure, inflation, consumer behaviour, competition among financial institutions, and a general trend to see the digitalisation of the economy could also affect the trends observed. Relative to the relatively short 2023–2025 observation period, some values were back calculated from official growth rates, and it is difficult to differentiate between permanent structural change and short-term fluctuations.

Policy priorities should thus be geared towards expansion and inclusion. There is need for enhanced cybersecurity, consumer protection, fee transparency, quick dispute-resolution systems and specific digital-literacy programmes as AZQR and the infrastructure for instant payments are developed further. Special care should be exercised towards the social-card holders, older users, rural communities etc. who may have difficulties accessing digital solutions. More data on anonymized and disaggregated payments across regions, age, income bands, banks, merchant groups and payment channels would also enhance future studies and result in a more robust evaluation of financial inclusion.

Overall, the evidence indicates a shift toward a more digital, traceable, and cashless financial system, which, however, will require aside from technological progress trust, accessibility, institutional endurance and capability of the users. Future studies could incorporate longer time-series and panel data and, if available, employ econometric tools that allow for the identification of the impact of digital-banking expansion in addition to other macroeconomic and institutional influences.

AUTHOR CONTRIBUTIONS

Conceptualization, U.A.; methodology, U.A. and E.S.; data collection, U.A.; formal analysis, U.A.; visualization, U.A.; writing—original draft, U.A.; supervision, E.S.; validation, E.S.; writing—review and editing, U.A. and E.S. 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 data analyzed in this study are publicly available from the official reports and statistical publications of the Central Bank of the Republic of Azerbaijan. No new primary dataset was generated during the study.

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Reconceptualizing human-nature relations in Islamic environmental ethics: A Qur'anic framework of ecological responsibility

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ABSTRACT

The escalating global environmental crisis has encouraged renewed attention to religious perspectives on the relationship between humans and the natural world. Within Islamic environmental ethics, stewardship has often been used to explain human responsibility towards creation, yet this approach can retain an anthropocentric understanding of human authority. This study examines this tension and develops a relational Qur'anic framework of ecological responsibility based on five concepts: *khalīfah* (succession and responsibility), *amānah* (trust), *umam* (communities of creation), *mīzān* (balance), and *fasād* (corruption and disorder). The study employs a qualitative, normative-theological, and comparative approach, using thematic-hermeneutical analysis of relevant Qur'anic passages and selected classical and contemporary Islamic scholarship. The analysis shows that these concepts, when considered together, place limits on human authority and connect human agency with responsibility, ecological balance, and accountability. The study argues that this integrated reading provides a broader understanding of ecological responsibility that extends beyond individual stewardship to questions of collective human conduct and environmental responsibility. This approach contributes to Islamic environmental ethics by bringing established Qur'anic concepts together into a coherent account of human–nature relations.

INTRODUCTION

The contemporary global environmental crisis represents a profound rupture in the moral and metaphysical systems that once governed the relationship between humanity and the natural world. Worsening climatic disruptions, accelerated biodiversity loss, soil degradation, and chemical toxicity are the material consequences of unsustainable, growth-oriented socio-economic practices. The Intergovernmental Panel on Climate Change (IPCC) notes that anthropogenic greenhouse gas emissions have caused a rapid increase in extreme weather events and deep systemic vulnerabilities across both human and non-human communities (IPCC, 2023). However, the ecological crisis has also been discussed as a crisis of values and worldview, particularly in critiques of approaches that treat nature primarily in terms of human utility (Nasr, 1996).

In response to this spiritual and philosophical impasse, academic attention has increasingly focused on world religions as rich repositories of ecological imagination, moral restraint, and collective action. Within the field of Islamic studies, a substantial body of literature has sought to reconstruct an ecological ethos based on the primary scriptural texts: the Qur'an and the Sunnah. This movement, often termed "Eco-Islam" or Islamic ecotheology, has largely focused on establishing the theological foundations for environmental responsibility (Abdelzaher et al., 2017). Scholars commonly assembled Qur'anic concepts such as the human vicegerency (khalīfah), and cosmic balance (mīzān) to argue that environmental care is an inherent religious obligation (Kula, 2011).

Despite these valuable contributions, contemporary Islamic environmental scholarship remains characterized by a significant conceptual limitation. A significant strand of contemporary Islamic environmental scholarship has been organised around a stewardship-oriented reading of *khalifah* as an unproblematic mandate for human ecological management (Nur et al., 2026). This reading, while pedagogically useful, often assumes that human vicegerency inherently implies environmental care, while under-analyzing its political history, semantic complexity, and anthropocentric implications. By framing humans as the privileged stewards of a passive natural world, this stewardship paradigm may inadvertently retain a hierarchical understanding in which nature remains primarily an object of human management. Furthermore, general appeals to individual piety and moderation fail to engage the systemic, structural, and distributive inequalities that drive the global ecological crisis.

This article addresses this conceptual tension by proposing a relational Qur'anic framework of ecological responsibility that systematically reconceptualizes human–nature relations. We argue that the Qur'anic concepts of khalīfah, amānah, umam, mīzān, and fasād cannot be understood through a simple model of human stewardship or mastery. Instead, they form a cohesive, relational ethic of ecological responsibility that understands human agency strictly through moral limitation, creaturely interdependence, and eschatological accountability. This framework is developed across four main dimensions: (1) khalīfah and the limits of human authority; (2) umam and the wider community of creation; (3) mīzān and ecological balance; and (4) fasād and collective environmental responsibility.

LITERATURE REVIEW

The discourse on Islam and ecology has developed considerably over the past few decades, with early scholarship examining the relationship between Islamic theology, sacred cosmology, and the natural world (Nasr, 1996). Early literature primarily focused on establishing the theological justification ("why") for environmental conservation. This established a foundation showing that because God is the absolute Owner and Sustainer of the cosmos (tawḥīd), nature possesses intrinsic value as a sign (āyah) of His presence, and human beings are assigned a custodial role (khalīfah) on earth (Haideri, 2025; Gueye & Mohamed, 2022). Subsequent scholarship has moved towards more practical questions, examining environmental responsibility in relation to specific areas such as water, land, plants, animals, business practice, and agriculture. Recently, empirical and thematic studies have attempted to move "beyond why" toward "what and how," analyzing specific environmental categories like water, air, land, plants, and animals and articulating behavioral guidelines for modern enterprise and agriculture (Helfaya et al., 2016).

A critical review of this rich literature reveals a persistent conceptual disconnect. As Nur et al. (2026) argue, the popular eco-Islamic translation of khalīfah as "environmental stewardship" carries inherent interpretive ambivalence. In its sovereigntist or heavily managerial forms, stewardship can function as a paternalistic paradigm that validates human moral sovereignty over the biosphere. This reading is vulnerable to the secular Western critique that monotheistic creeds inherently desacralize and exploit nature by placing humans at the absolute center of value (White, 1967). While several scholars have attempted to correct this anthropocentrism by asserting divine ownership, they often retain the human being as the exclusive active agent authorized to represent the interests of a passive creation (Nur et al., 2026).

Previous studies have examined *khalīfah*, *amānah*, *mīzān*, and related Qur'anic principles in discussions of stewardship, conservation, and environmental responsibility. However, these concepts are often considered separately or within broader discussions of Islamic environmental ethics. Less attention has been given to how *khalīfah*, *amānah*, *umam*, *mīzān*, and *fasād* can be considered together in explaining human responsibility, ecological balance, and accountability within the wider creation. This leaves room for a more integrated account of human–nature relations grounded in the Qur'anic framework.

This study addresses this gap by examining five Qur'anic concepts, *khalīfah*, *amānah*, *umam*, *mīzān*, and *fasād*, within a single conceptual framework of ecological responsibility. It considers their meanings in Qur'anic context and examines relevant interpretations in classical and contemporary Qur'anic interpretations. The study then considers how these concepts relate to human responsibility, ecological balance, and accountability, offering an integrated understanding of human–nature relations within Islamic environmental ethics.

1. How do the Qur'anic concepts of *khalīfah*, *amānah*, *umam*, *mīzān*, and *fasād* shape an Islamic understanding of human–nature relations?
2. How can these concepts be brought together into a coherent framework of ecological responsibility?

MATERIALS AND METHODS

This research is qualitative and mainly concerned with the interpretation of Islamic environmental ethics. It uses a thematic-hermeneutical design (*tafsīr mawḍūʿī*) to examine five central Qur'anic concepts: *khalīfah*, *amānah*, *umam*, *mīzān*, and *fasād*.

The analysis proceeds in three stages. First, the meanings and conceptual dimensions of these terms are examined through relevant classical and contemporary Qur'anic interpretations. Second, their Qur'anic contexts and interpretations are compared across selected classical and contemporary exegetical works. Third, the recurring ethical principles are synthesised to identify their implications for human–nature relations, ecological balance, responsibility, and accountability. These findings are then used to develop the proposed conceptual framework of ecological responsibility.

RESULTS AND DISCUSSION

Khalīfah and the limits of human authority

The Qur'an introduces the concept of *khalīfah* in Surah Al-Baqarah (2:30),

وَإِذْ قَالَ رَبُّكَ لِلْمَلَائِكَةِ إِنِّي جَاعِلٌ فِي الْأَرْضِ خَلِيفَةً قَالُوا أَتَجْعَلُ فِيهَا مَنْ يُفْسِدُ فِيهَا
وَيَسْفِكُ الدِّمَاءَ وَنَحْنُ نُسَبِّحُ بِحَمْدِكَ وَنُقَدِّسُ لَكَ قَالَ إِنِّي أَعْلَمُ مَا لَا تَعْلَمُونَ

where God announces the placing of a *khalīfah* on the earth. Contemporary discussions of Islamic environmental ethics often understand this concept in terms of human stewardship of the earth (Pathan & Seth, 2025; Haideri, 2025). Classical interpretations, however, provide a broader understanding of *khalīfah*. Al-Ṭabarī relates the term to succession, while other exegetical interpretations connect human presence on earth with its cultivation and the ordering of human affairs (Nur et al., 2026). The same Qur'anic passage also records the angels' concern that humanity may cause corruption (*yufsidu*) and shed blood. This introduces an important qualification to the idea of human authority, showing that human agency carries the possibility of both constructive and harmful action.

The concept of *khalīfah* can therefore be understood alongside the Qur'anic emphasis on human accountability. This becomes clearer when it is considered together with *amānah*, the trust described in Surah Al-Aḥzāb (33:72).

إِنَّا عَرَضْنَا ٱلْأَمَانَةَ عَلَى ٱلسَّمَٰوَٰتِ وَٱلْأَرْضِ وَٱلْجِبَالِ فَأَبَيْنَ أَن يَحْمِلْنَهَا وَأَشْفَقْنَ مِنْهَا وَحَمَ
لَهَا ٱلْإِنسَٰنُ ۖ إِنَّهُۥ كَانَ ظَلُومًا جَهُولًا

The verse presents the trust as something that the heavens, the earth, and the mountains declined to bear, while humanity accepted it. The description of the human being as *ẓalūman* and *jahūlan* further draws attention to the moral responsibility and vulnerability associated with bearing this trust (Nur et al., 2026). In this reading, *khalīfah* does not simply confer authority over the earth; it places human agency within a framework of responsibility and accountability.

Taken together, *khalīfah* and *amānah* suggest that the human relationship with the natural world should not be understood only in terms of possession or control. Human use of natural resources is accompanied by responsibilities concerning restraint, care, and accountability. This understanding provides an important basis for considering human–nature relations within Islamic environmental ethics.

Umam and the Wider Community of Creation

The Qur'an also presents non-human creatures as part of the wider order of creation. In Surah Al-Anʿām (6:38),

وَمَا مِن دَآبَّةٍۢ فِى ٱلْأَرْضِ وَلَا طَـٰٓئِرٍۢ يَطِيرُ بِجَنَاحَيْهِ إِلَّآ أُمَمٌ أَمْثَالُكُم ۚ مَّا فَرَّطْنَا فِى ٱلْكِتَـٰبِ مِن شَىْءٍۢ ۚ ثُمَّ إِلَىٰ رَبِّهِمْ يُحْشَرُونَ

"All living beings roaming the earth and winged birds soaring in the sky are communities like yourselves. We have left nothing out of the Record. Then to their Lord they will be gathered all together." Animals and other creatures are described as communities (*umam*) like human communities. This verse gives non-human life a visible place within the Qur'anic understanding of creation and suggests that animals are not simply objects of human use (Abu-Rayash & Sabbah, 2023). Their existence is also connected to the wider divine order, in which God creates, sustains, and ultimately gathers His creatures (Kholis & Aulassyahied, 2022).

This understanding is further reflected in the Qur'anic description of creation as engaged in the glorification of God. Surah Al-Isrāʾ (17:44)

تُسَبِّحُ لَهُ ٱلسَّمَـٰوَٰتُ ٱلسَّبْعُ وَٱلْأَرْضُ وَمَن فِيهِنَّ ۚ وَإِن مِّن شَىْءٍ إِلَّا يُسَبِّحُ بِحَمْدِهِۦ وَلَـٰكِن لَّا تَفْقَهُونَ تَسْبِيحَهُمْ ۗ إِنَّهُۥ كَانَ حَلِيمًا غَفُورًۭا

states that the seven heavens, the earth, and all those in them glorify Him. There is not a single thing that does not glorify His praises, but you ˹simply˺ cannot comprehend their glorification. He is indeed Most Forbearing, All-Forgiving, while other verses refer to the prostration of creatures, including birds, stars, and trees (Surah Al-Hajj 22:18).

أَلَمْ تَرَ أَنَّ ٱللَّهَ يَسْجُدُ لَهُۥ مَن فِى ٱلسَّمَـٰوَٰتِ وَمَن فِى ٱلْأَرْضِ وَٱلشَّمْسُ وَٱلْقَمَرُ وَٱلنُّجُومُ وَٱلْجِبَالُ وَٱلشَّجَرُ وَٱلدَّوَآبُّ وَكَثِيرٌ مِّنَ ٱلنَّاسِ ۖ وَكَثِيرٌ حَقَّ عَلَيْهِ ٱلْعَذَابُ ۗ وَمَن يُهِنِ ٱللَّهُ فَمَا لَهُۥ مِن مُّكْرِمٍ ۚ إِنَّ ٱللَّهَ يَفْعَلُ مَا يَشَآءُ

"Do you not see that to Allah bow down ˹in submission˺ all those in the heavens and all those on the earth, as well as the sun, the moon, the stars, the mountains, the trees, and ˹all˺ living beings, as well as many humans, while many are deserving of punishment. And whoever Allah disgraces, none can honour. Surely Allah does what He wills." And in Surah An- Nur 24:41

أَلَمْ تَرَ أَنَّ ٱللَّهَ يُسَبِّحُ لَهُۥ مَن فِى ٱلسَّمَـٰوَٰتِ وَٱلْأَرْضِ وَٱلطَّيْرُ صَـٰٓفَّـٰتٍۢ ۖ كُلٌّۭ قَدْ عَلِمَ صَلَاتَهُۥ وَتَسْبِيحَهُۥ ۗ وَٱللَّهُ عَلِيمٌۢ بِمَا يَفْعَلُونَ ٤١

"Do you not see that Allah is glorified by all those in the heavens and the earth, even the birds as they soar? Each ˹instinctively˺ knows their manner of prayer and glorification. And Allah has ˹perfect˺ knowledge of all they do." These passages present the natural world not merely as a resource for human use, but as part of a wider order of creation that has its own relationship with God (Pathan & Seth, 2025).

From an environmental perspective, the concept of *umam* therefore broadens the way human beings can understand their relationship with other forms of life. When considered alongside the Qur'anic portrayal of creation as signs of God (*āyāt*), it supports an understanding of nature in which non-human life has significance beyond its usefulness to humans (Zaman et al., 2026). The protection of species and habitats can consequently be understood not only in terms of preserving resources for human societies, but also as part of the responsibility to respect the wider community of creation.

Mīzān and Ecological Balance

The Qur'an presents *mīzān* as an important part of the order established by God. In Surah al-Raḥmān (55:7–9),

وَٱلسَّمَآءَ رَفَعَهَا وَوَضَعَ ٱلْمِيزَانَ أَلَّا تَطْغَوْا۟ فِى ٱلْمِيزَانِ وَأَقِيمُوا۟ ٱلْوَزْنَ بِٱلْقِسْطِ وَلَا تُخْسِرُوا۟ ٱلْمِيزَانَ

"As for the sky, He raised it ˹high˺, and set the balance ˹of justice˺so that you do not defraud the scales. Weigh with justice, and do not give short measure."

God is described as having raised the heaven and established the balance, followed by the instruction not to transgress this balance and to maintain justice in measurement. The term *mīzān* therefore carries both the sense of balance and of justice in human dealings. Classical interpretations also connect the passage with fairness and the avoidance of excess and injustice (Reflita et al., 2025). When considered in relation to environmental ethics, *mīzān* can be understood as providing a basis for relating the order of creation to responsible human conduct (Nur et al., 2026).

The Qur'anic idea of balance is also connected with the measured and proportionate character of creation. References to God creating things according to measure (*qadr*) and due proportion (Qur'an Surah Al-Hijr (15:19)

وَٱلْأَرْضَ مَدَدْنَـٰهَا وَأَلْقَيْنَا فِيهَا رَوَٰسِىَ وَأَنۢبَتْنَا فِيهَا مِن كُلِّ شَىْءٍۢ مَّوْزُونٍۢ

"As for the earth, We spread it out and placed upon it firm mountains, and caused everything to grow there in perfect balance." And in the Qur'an, Surah Al-Qamar (54:49)

إِنَّا كُلَّ شَيْءٍ خَلَقْنَاهُ بِقَدَرٍ

" Indeed, We have created everything, perfectly preordained." reinforce this understanding. From an environmental perspective, these verses can be read as encouraging restraint in human use of the natural world. Practices such as excessive consumption (*isrāf*), wastefulness (*tabdhīr*), and harmful use of resources are therefore difficult to reconcile with an ethic that values balance and moderation (Rizk, 2014). In this sense, *mīzān* strengthens the idea that human needs and economic activities should be pursued without disregarding the wider conditions of creation.

This interpretation also gives *mīzān* relevance to contemporary environmental concerns. Measures concerning resource use, pollution, and ecological limits can be understood as practical expressions of the broader ethical concern for maintaining balance. The concept therefore provides a basis for questioning forms of economic activity that place excessive pressure on natural systems and for encouraging more restrained and responsible patterns of resource use (Nur et al., 2026; Radiyal et al., 2025).

Fasād and Collective Environmental Responsibility

The primary Qur'anic term for ecological disruption is fasād (corruption, mischief, or ruin). Surah Ar-Rūm (30:41)

ظَهَرَ ٱلْفَسَادُ فِى ٱلْبَرِّ وَٱلْبَحْرِ بِمَا كَسَبَتْ أَيْدِى ٱلنَّاسِ لِيُذِيقَهُم بَعْضَ ٱلَّذِى عَمِلُوا۟ لَعَلَّهُمْ يَرْجِعُونَ

establishes a direct, causal connection between human conduct and ecological degradation: "Corruption has spread on land and sea as a result of what people's hands have done, so that Allah may cause them to taste ˹the consequences of˺ some of their deeds and perhaps they might return ˹to the Right Path˺." Linguistically, the root fa-sa-da denotes taking something out of its established state of balance and harmony (*ṣāliḥ*) (Reflita et al., 2025). Classical exegesis (such as Al-Ṭabarī and Al-Qurṭubī) traditionally interpreted *fasād* as moral deviance, social injustice, and physical drought or degradation of the land (Nur et al., 2026). In a modern context, this causal framing offers a powerful spiritual diagnosis of the ecological crisis, showing that environmental disasters and climatic disturbances are direct outcomes of collective human actions and ethical deviations (Esdarwati, 2025).

Significantly, the Qur'an frames *fasād* not merely as individual moral failure, but as a collective and structural responsibility. Using plural and organized verb forms (such as *yufsidu* and *tufsidū*), the scriptural text targets systemic, large-scale destruction and developmental models driven by arrogance and greed (*umamun al-mufsidīn*). The prohibition of spreading corruption on earth after it has been set in order (*lā tufsidu fī al-arḍ;* Qur'an 7:56) is a central legal and theological command. (Esdarwati, 2025). This command is paired with a sharp critique of extravagant actors *(al-musrifīn)* who consume natural resources beyond their basic needs, concentrate wealth and power, displace vulnerable populations, and destroy ecosystems (Qur'an 26:151-152).

وَلَا تُطِيعُوٓا۟ أَمْرَ ٱلْمُسْرِفِينَ ٱلَّذِينَ يُفْسِدُونَ فِى ٱلْأَرْضِ وَلَا يُصْلِحُونَ

"And do not follow the command of the transgressors, who spread corruption throughout the land, never setting things right." The Qur'anic response to *fasād* is an active call for ecological repentance (*tawbah*) and restorative reform (*iṣlāḥ*). True restoration requires transforming the material, financial, and political systems that organize excess. It demands that human resource use operate within corridors of collective welfare (*maslaḥah*) and restorative transformation. This structural shift moves Islamic environmental ethics beyond a 'soft' individualist moralizing toward a robust, collective framework for structural accountability and ecological reform (Esdarwati, 2025).

CONCLUSIONS

This study has reconceptualised human–nature relations within Islamic environmental ethics through an examination of five Qur'anic concepts: *khalīfah*, *amānah*, *umam*, *mīzān*, and *fasād*. Considered together, these concepts present human agency not as unrestricted authority over nature, but as a form of responsibility accompanied by accountability and restraint. *Khalīfah* places human agency within a position of responsibility, while *amānah* emphasises the moral burden associated with that responsibility. The concept of *umam* draws attention to the wider community of creation, including non-human life, while *mīzān* provides an ethical basis for balance and moderation. *Fasād*, in turn, highlights the consequences of human actions that disturb this order.

The study therefore argues that these concepts are most meaningful when understood in relation to one another rather than as separate environmental principles. Together, they provide a broader account of ecological responsibility in which human beings remain part of creation while bearing particular moral responsibilities within it. This reading also moves the discussion beyond a narrow understanding of environmental care as individual stewardship and places greater emphasis on the relationship between human conduct, ecological balance, and accountability.

The framework developed here contributes to Islamic environmental ethics by bringing established Qur'anic concepts together to provide a more integrated understanding of human–nature relations. At the same time, the study remains conceptual and interpretive. It does not empirically test the framework or assess its application in particular environmental institutions or policies. Further research can therefore examine how the framework may be interpreted and applied in specific social, legal, educational, and environmental contexts.

The Qur'anic framework developed in this study also has implications for environmental practice in contemporary Muslim societies. Several areas may benefit from greater engagement with these principles:

- Institutionalizing Environmental Fiqh in Public Policy: Governments and regulatory bodies in Muslim-majority countries could integrate Qur'anic ecological principles, such as the prohibition of *fasād* and the preservation of *mīzān*, into environmental legislation, environmental impact assessments, and resource extraction licensing
- Reforming Islamic Financial Standards (Green Finance): Islamic Financial Institutions (IFIs) could incorporate environmental criteria into project financing, corporate investment, and asset allocation, with greater attention to ecological risks and environmental impacts.
- Curriculum Reform in Islamic Education: Educational curricula across madrasas, public schools, and universities should be updated to integrate this relational Qur'anic framework. Traditional theological education should bridge scripture with environmental science, framing ecological preservation as a core dimension of faith *(īmān)* and collective worship.
- Establishing Community Conservation Zones: Local and regional authorities should revive traditional land-management systems, such as *himā* (protected ecological sanctuaries) and *ḥarīm* (resource buffer zones), to protect watersheds, rangelands, and endangered species from urban encroachment and industrial degradation.

Ultimately, this critical Qur'anic framework demonstrates that responses to the global ecological crisis need not sacrifice fidelity to religious tradition. By drawing upon the spiritual, legal, and ethical resources of the Qur'anic tradition, contemporary Muslim societies can develop forms of environmental thinking that remain rooted in Islamic values while responding to contemporary ecological challenges.

AUTHOR CONTRIBUTIONS

Conceptualization, M.S. and T.B.T; methodology, M.S. and M.U.; analysis, M.U. and T.B.T; writing, T.B.T; original draft preparation, M.S. and M.U; review and editing, M.S.; supervision, T.B.T. All authors have read and agreed to the final version of the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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DATA AVAILABILITY STATEMENT

This study is conceptual and does not involve the collection or generation of empirical datasets. The analysis is based on Qur'anic texts and published scholarly literature cited in the manuscript. Accordingly, no original dataset was generated or analysed for this study.

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Financial performance evaluation of Tesla, Inc. using integrated ratio and DuPont analysis for 2021–2025

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ABSTRACT

The financial performance of Tesla, Inc. from 2021 to 2025 is analyzed using a case-study approach that includes ratio analysis, three-step DuPont decomposition, cash-flow indicators, a specific adjustment for the 2023 tax benefit, and a 2025 peer comparison with BYD, Ford and General Motors. The analysis is based on annual filings audited and adjusted by average levels of assets and equity if necessary. As per the results, Tesla's operating profitability and asset utilization have been declining since 2022, with the worst results being witnessed in 2024. The approximately $5.93 billion difference was due to a non-cash one-time tax benefit, materially affecting reported 2023 net income of $15.00 billion. Once they remove this figure for diagnostic purposes, net income drops to $9.07 billion, net margin to 9.37%, ROA to 9.60% and ROE to 16.89%. By 2025, operating margin fell to 4.59%, ROE to 4.89%, operating current ratio to 2.16 and liabilities-to-equity to an still relatively low 0.67. Operating cash flow remained positive in all years and FCF bounced back to approximately $6.22 billion in 2025. Based on the peer comparison, Tesla has a combination of strong liquidity, conservative liability profile, and below-average shareholder returns compared to BYD, and slightly below-average ROE compared to General Motors. The results are meant to be a diagnosis of the firm's finances and not an inference on the industry.

INTRODUCTION

Financial statements are extensively used in management, investment analysis, credit evaluation, and strategic planning, as they give a structured look into a firm's profitability, liquidity, financing, and how these funds are being used. Revenue and net income are not adequate for this purpose, as they demonstrate scale, but not whether or not a growing asset base is generating proportional returns. This is the limitation that the ratio analysis resolves by connecting items on the income statement, balance sheet and cash-flow statement. Previous research demonstrated the usefulness of accounting ratios to measure financial condition and the risk of failure (Beaver, 1966; Altman, 1968; Ohlson, 1980), and subsequent research related structured financial-statement analysis to profitability forecasting and equity valuation (Nissim & Penman, 2001).

The greatest interpretive difficulty lies in the fact that individual ratios can go up or down. A firm can increase its liquidity and decrease its profitability, or it can decrease its leverage and decrease the return on equity (ROE) as earnings grow more slowly than the equity base. In this context it is helpful to use the three-part DuPont identity which decomposes ROE into net profit margin, total asset turnover, and the equity multiplier. This breakup allows one to identify changes due to operating profitability, asset productivity and financing structure. Previous studies also indicate that the importance of these components varies by sector and institutional context (Bunea et al., 2019; Weidman et al., 2019; Jape & Malhotra, 2023), and that DuPont information can be important to market participants (Soliman, 2008).

The second is the quality of reported profits. Some accounting items are not recurring, and can significantly impact net income, and accruals-based profitability measures don't necessarily indicate whether the business is producing sufficient cash to invest. Therefore, the profitability ratios in the present study are read in conjunction with the operating cash flow, free cash flow and capital-expenditure coverage. It also disclosing a large one-time item in 2023, Tesla's approximately $5.93 billion non-cash tax benefit due to the release of a valuation allowance on certain deferred tax assets (Tesla, Inc., 2024).

Tesla is analyzed not as a representative sample of the automotive sector but as a firm that was purposefully chosen. These activities span the range of electric-vehicle production, energy generation and storage, which situates the issue of capital efficiency and financial resilience in a transition-oriented business context. The period 2021-2025 is particularly revealing as it encompasses a period of growth and margin expansion, the tax-related earnings anomaly in 2023 and a subsequent period of continued asset growth with a decline in operating profitability. The company's audited U.S. GAAP filings also offer a consistent and repeatable analysis data trail.

The study thus investigates four questions: (1) what were the changes in Tesla's profitability, effectiveness, liquidity, financing structure, and cash-generation from 2021 to 2025; (2) what are the components of the changes in ROE; (3) what is the impact of the disclosed one-time tax benefit on the assessed ROE, after being arithmetically removed; and (4) how does Tesla's ratio profile compare to BYD, Ford and GM in 2025? The contribution is not a new financial ratio. Instead, the paper incorporates trend analysis, annual DuPont decomposition, disclosure item earnings adjustment, cash-flow checks and peer benchmarking in one straightforward case-study format.

LITERATURE REVIEW

Financial ratio analysis has long been applied to various aspects of company's financial position. Beaver (1966) was able to identify systematic difference between the financial ratios of failed firms and non-failed ones, while Altman (1968) combined accounting measures in a discriminant model, Ohlson (1980) came up with a probabilistic approach in which size, financial structure, performance, and liquidity are part of the model. Those studies investigated distress prediction, but the principle they had pointed to was one important to the current analysis: it is better to consider ratios together, than to consider them separately.

Subsequent studies focused more on operating diagnosis and valuation. Nissim & Penman (2001) suggested to apply the hierarchical method in which operating and financing activities are separated, and in which current accounting information is utilized to determine future profitability and equity payoffs. This separation is important to ROE as a shift in the ratio can be caused by improved operations, a shift in capital structure, or a shift in the equity denominator. So, a decomposition is required before the economic significance of an increase or decrease in ROE can be determined.

The Decomposition can be done using the DuPont framework. ROE can be written in its traditional three step format as a combination between net profit margin, total asset turnover and the equity multiplier. The three components relate in general to profitability, the efficient use of resources and the financing structure. Jin (2017) reports that information in DuPont components is relevant to the future ROE, Davidson (2020) discusses their diagnostic nature, and Soliman (2008) indicates their relevance to market participants. The extended DuPont analysis has also been used in other more recent research to measure manufacturing performance (Endris & Babu, 2026). Thus, the framework does not reveal anything new about the accounting identity, but does make the causes of changes in shareholder returns more transparent.

Experience has also shown by empirical studies that one DuPont factor cannot always be considered to be the most important. When looking at the Romanian energy companies, Bunea et al. (2019) consider that asset turnover and financial leverage are relevant for the ROE indicator. For manufacturing firms in the U.S., Germany and Japan, profit margin is a significant determinant and the importance of turnover and leverage are different in different settings, according to Weidman et al. (2019). Jape and Malhotra (2023) also find that the constituent items of ROE are decision relevant. These results suggest that it is possible to combine within-company trends with external peer context.

There is an additional dimension in the diagnosis as short-term financial capability and profitability may not necessarily go hand in hand. The literature on working-capital management finds systematic relationship between working-capital efficiency and firm profitability (Singh et al., 2017; Yasmin & Mohiuddin, 2021; Jaworski & Czerwonka, 2024). However, having too much liquidity buffer can also have opportunity cost, meaning that a higher current ratio does not necessarily imply a greater economic efficiency (Silva & Silva, 2026).

For a capital intensive company cash flow evidence is especially valuable. Positive accounting earnings does not necessarily mean that the cash generated from interior operations is adequate to fund investment. Operating cash flow and free cash flow serve as cross-checks on the profit derived from accruals and capital expenditure is a measure of the investment burden on the cash generated internally. These are meant to be supplementary to the profitability, efficiency and financing ratios.

This is a narrow research gap. The reported performance can be described using conventional ratio and DuPont analysis, but if cash-generation capacity is considered and the results are compared with a peer benchmark, a firm level diagnosis becomes more informative when the examination is completed with one material one-off accounting item. The present paper aims to fill that gap with a cross-check of the reported ratios with an adjusted 2023 profitability measure, full annual DuPont components, cash-flow indicators and a 2025 comparison with three key automotive peers.

This design also sets the boundaries of the claims that may be made. The study has only five observations per year for one focal company and causal relationships or sector-wide effects cannot be estimated, and formal inferential tests would suggest more precision than can be warranted by the data. Rather, the intention is to offer a diagnostic framework that can be reproduced, and that in the future could be expanded to multi-company panel data to which statistical testing and industry adjusted benchmarking would be more suitable.

MATERIALS AND METHODS

A quantitative longitudinal case-study design is adopted to assess Tesla, Inc. for the 5 fiscal periods 2021-2025. The company is viewed as a diagnostic case because they produce their products on a large scale for the automotive industry, they have an energy-oriented business, have had dramatic changes in their capital base and have consistent and available audited U.S. GAAP filings. The time interval is materially different operating conditions and within-firm comparison of profitability, use of assets, financing, liquidity, and cash generation is possible.

The data for Tesla comes from audited Form 10-K with the U.S. Securities and Exchange Commission for FY21-FY25 (Tesla, Inc., 2022, 2023, 2024, 2025, 2026). All numbers are in millions of U.S. dollars (USD) and include extracted items: revenue, operating income, net income attributable to common stockholders, current assets, current liabilities, total assets, total liabilities, stockholders' equity, net cash provided by operating activities, and capital expenditures. The peer comparison for 2025 is based on information in annual reports of the following companies: BYD Company Limited (BYD Company Limited, 2026), Ford Motor Company (Ford Motor Company, 2026), and General Motors Company (General Motors Company, 2026). So it is a ratio compare and no currency conversion takes place.

There are five analytical areas for the indicator set. Profitability includes operating margin, net profit margin, return on assets (ROA), and ROE; efficiency includes total asset turnover; liquidity includes current ratio; financing structure includes total liabilities/total stockholders' equity; and cash generation includes operating cash flow, free cash flow, operating-cash-flow margin, and capital-expenditure margin. The financing measure is called liabilities-to-equity and not debt-to-equity as the numerator consists of all liabilities reported. ROE is then broken down using the three step DuPont identity.

$$\textit{Operating margin} = \textit{Income from operations} / \textit{Revenue} \times 100 \quad (1)$$

$$\textit{Net profit margin} = \textit{Net income attributable to common stockholders} / \textit{Revenue} \times 100 \quad (2)$$

$$\textit{ROA} = \textit{Net income attributable to common stockholders} / \textit{Average total assets} \times 100 \quad (3)$$

ROE = Net income attributable to common stockholders / Average stockholders' equity × 100 (4)

Asset turnover = Revenue / Average total assets (5)

Current ratio = Current assets / Current liabilities (6)

Liabilities-to-equity = Total liabilities / Stockholders' equity (7)

ROE = Net profit margin × Asset turnover × Equity multiplier (8)

Operating cash flow margin = Net cash provided by operating activities / Revenue × 100 (9)

Free cash flow = Net cash provided by operating activities − Capital expenditures (10)

CapEx-to-operating-cash-flow = Capital expenditures / Net cash provided by operating activities × 100 (11)

The average total assets and average stockholders' equity represent the average of year-end and beginning fiscal year balances. The comparative balances for 2020 appear in Tesla's 2021 Form 10-K for use in calculating average values for 2021 (Tesla, Inc., 2022). Calculations trail was preserved for the reproduction of each ratio. The 2025 filing, for instance, includes a total asset balance of $122,070 million at the end of 2024 and $137,806 million at the end of 2025, and stockholders' equity of $72,913 million and $82,137 million, respectively. In 2025, Tesla's total revenue was $94,827 million, net income for common stockholders was $3,794 million, current assets were $68,642 million, current liabilities were $31,714 million, and total liabilities were $54,941 million (Tesla, Inc., 2026). These numbers result in an average of $129,938 Million in assets and $77,525 Million in equity. The resulting 2025 ratios are ROA 2.92%, ROE 4.89%, asset turnover 0.73, current ratio 2.16, and liabilities-to-equity 0.67. The same procedure is applied to each year.

The tax effect for 2023 is reported separately since it has a material impact on reported net income. Tesla released the valuation allowance for U.S. federal and certain state deferred tax assets of $6.54 billion and estimates the valuation allowance for the portion of deferred tax assets to be realized in future years of approximately $5.93 billion (Tesla, Inc., 2024). Reported net income for 2023 is therefore adjusted by $5.930 billion to reach an amount of $9.067 billion for diagnostic purposes. Using the same revenue, average-asset, and average-equity denominators, net margin, ROA, and ROE are then re-calculated. This adjustment eliminates only the item of tax that was disclosed and is not to be considered as a fully normalized earnings measure.

The analysis is conducted in seven stages: looking at the raw financial data; calculating the ratios; analysing the trends over 5 years and growth rates; performing the annual Du Pont decomposition; adjusting for the 2023 effect of the tax system; comparing to cash flow indicators; and checking 2025 peer benchmark. Peer ratios are based on information from each company's own annual report and are calculated using the same conceptual formulas, as the items necessary to calculate the ratio are available. Due to divergent accounting practices, business mix, financial-services exposures and geography, the peer exercise is not a formal ranking or statistical test but a contextual comparison.

A mechanical sensitivity exercise is done using the ratios from the selected year in the accounting base (2022) and applying them to the accounting base 2025. Only arithmetic examples are given of these calculations. They are not models, they do not simulate prices, production capacities, product mix, competition, demand, macro-economic conditions, or management responses, nor are they forecasts or causal counterfactuals. These are only intended to demonstrate the accounting size of the margin and asset turnover change.

There are a few drawbacks to the design. Causal relationships and meaningful inferential testing cannot be derived from a 5-year case of single company. The analysis does not consider market based performance, environmental impacts, segment economics or risk adjusted cost of capital. The 2025 peer comparison provides an external perspective, but differences in accounting classification or business model do not go away. The findings should then be interpreted as clear and open financial diagnosis for a particular firm.

RESULTS AND DISCUSSION

Tesla's size grew significantly during the study period, but during that time the earnings trajectory did not track with that of revenues. As shown in Table 1, revenue increased from $53.82 billion in 2021 to $96.77 billion in 2023, was almost unchanged in 2024, and then declined to $94.83 billion in 2025. Net income grew at a faster pace until 2024, when it dropped to $7.09 billion and $3.79 billion in 2025. Revenue growth isn't a sufficient measurement of financial performance, as demonstrated by the divergence after 2023.

Table 1. Revenue and net income, 2021–2025 (USD millions)

Year	Revenue	Net income
2021	53,823	5,519
2022	81,462	12,556
2023	96,773	14,997
2024	97,690	7,091
2025	94,827	3,794

Source: Author's calculations based on Tesla, Inc. Form 10-K filings (2022–2026).

This change in direction is also reflected in the annual growth rates. Revenue grew by 51.4% in 2022 and 18.8% in 2023, slowed to 0.9% in 2024, and declined by 2.9% in 2025. The 2023 net-income figure is impacted by the tax benefit the company disclosed, so don't take the seeming peak in bottom-line profitability literally without the adjustment below.

Table 2. Balance-sheet scale, 2021–2025 (USD millions)

Year	Total assets	Stockholders' equity
2021	62,131	30,189
2022	82,338	44,704
2023	106,618	62,634
2024	122,070	72,913
2025	137,806	82,137

Source: Author's calculations based on Tesla, Inc. Form 10-K filings (2022–2026).

As seen from Table 2, growth of the balance sheet was faster than revenue. Total assets grew from $62.13 billion in 2021 to $137.81 billion in 2025, and stockholders' equity grew from $30.19 billion to $82.14 billion. With an increasing capital base, it required more revenue and earnings to achieve the ROA, ROE and asset turnover percentages seen before. This "denominator effect" is at the heart of the subsequent drop in return measures.

Table 3. Liquidity and liabilities-to-equity indicators

Year	Current ratio	Liabilities/equity

2021	1.38	1.01
2022	1.53	0.82
2023	1.73	0.69
2024	2.02	0.66
2025	2.16	0.67

Source: Author's calculations based on Tesla, Inc. Form 10-K filings (2022–2026).

Despite a deterioration in profitability, liquidity and financing structure improved. The current ratio increased from 1.38 in 2021 to 2.16 in 2025, while liabilities-to-equity fell from 1.01 to 0.67. It is important to note that the numerator represents total liabilities, not just interest-bearing debt, thus accounting for the label liabilities-to-equity. The pattern suggests that there was a greater cushion of short-term liquidity and a higher ratio of equity to the balance sheet, but not that the expanded capital base was being more effective. This separation is in line with the literature on working capital where liquidity and profitability are correlated but different aspects of performance (Singh et al., 2017; Jaworski & Czerwonka, 2024).

Table 4. Profit margins, 2021–2025

Year	Operating margin	Net margin
2021	12.12%	10.25%
2022	16.76%	15.41%
2023	9.19%	15.50%
2024	7.24%	7.26%
2025	4.59%	4.00%

Source: Author's calculations based on Tesla, Inc. Form 10-K filings (2022–2026).

Operating margin reached 16.76% in 2022 and then declined to 9.19% in 2023, 7.24% in 2024, and 4.59% in 2025. In 2023, the net margin was still abnormally high due to the impact of the one-time tax effect, with the operating margin also declining in the same direction by 2024-2025. In the same way, operating margin is a better indicator of the deteriorating underlying profitability after 2022.

Table 5. Return and efficiency indicators

Year	ROA	ROE	Asset turnover
2021	9.66%	21.06%	0.94
2022	17.38%	33.53%	1.13
2023	15.88%	27.94%	1.02
2024	6.20%	10.46%	0.85
2025	2.92%	4.89%	0.73

Source: Author's calculations based on Tesla, Inc. Form 10-K filings (2022–2026).

Both return and efficiency measures in Table 5 indicate this trend. ROA declined from 17.38% in 2022 to 2.92% in 2025, ROE fell from 33.53% to 4.89%, and asset turnover decreased from 1.13 to 0.73. Between 2021 and 2025, the assets increased at an average rate of approximately 22.0% annually, while the revenue increased at an average rate of approximately 15.2% annually, resulting in a decreasing ratio of revenue per dollar of average assets.

In combination, the decrease in margin and the decrease in turnover is more telling than either of them alone. It indicates that at lower performance, return, there was also a decrease in profit conversion ratio and a decrease in capital productivity, and the decrease in liability intensity is a less likely cause to explain the deterioration. This is consistent with earlier research on DuPont by other researchers which indicated that ROE depends on the interplay of margin, turnover and leverage, and the proportion of each of these factors varies among companies and contexts (Bunea et al., 2019; Weidman et al., 2019).

The profitability ratios for the five years were plotted in Fig.1. Net margin, ROA, and ROE for the 2023 observation are marked with an asterisk because the results have been calculated without the disclosed $5.93 billion non-cash tax benefit; Table 6 reflects the diagnostic values after excluding this non-cash tax benefit.

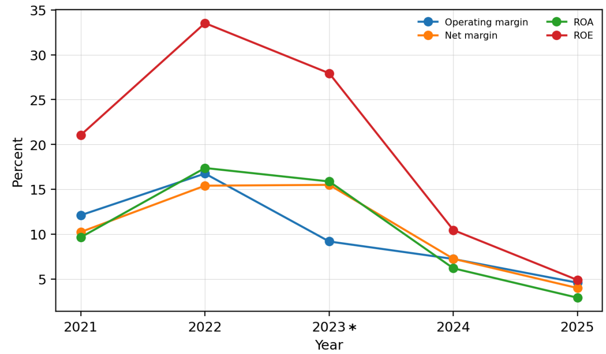

Figure 1. Trend in key profitability ratios, 2021–2025

The data are the author's projections based on form 10-K filings from Tesla. Note: * 2023 net margin, ROA and ROE include an approximately $5.93 billion one-time non-cash tax benefit; adjusted net margin, ROA and ROE is shown in Table 6.

The stated $5.93 billion tax benefit has a material impact on the 2023 reading. Diagnostic net income falls to $9.07 billion, with a net margin of 9.37%, ROA of 9.60%, and ROE of 16.89%. This is significantly lower than the return reported in 2023, which was measured, and is closer to the operating margin decline already seen. Given this context, 2023 should be viewed more as a transition year rather than as an unequivocal year of peak profitability.

Table 6. Reported and tax-effect-adjusted 2023 profitability

Measure	Reported 2023	Tax-effect adjustment	Diagnostic adjusted
Net income (USDm)	14,997	−5,930	9,067
Net margin	15.50%	—	9.37%
ROA	15.88%	—	9.60%
ROE	27.94%	—	16.89%

Source: Author's calculations based on Tesla, Inc. (2024). Note: the adjustment subtracts only the disclosed $5.93bn non-cash tax benefit and is not a fully normalized earnings measure.

Table 7 provides a DuPont decomposition that helps identify the sources of the ROE's change. ROE in 2022 was higher at 33.53%, despite a fall in the equity multiplier, as a result of the rise in net margin and asset turnover. Net margin dropped to 4.00% and asset turnover to 0.73 by 2025 and the equity multiplier was 1.68. The decrease in ROE can hence be attributed primarily to lower profitability and asset utilization and not financial leverage. This is the diagnostic significance of the DuPont framework which has been highlighted in earlier studies (Jin, 2017; Soliman, 2008).

Table 7. Three-step DuPont decomposition, 2021–2025

Year	Net margin	Asset turnover	Equity multiplier	ROE
2021	10.25%	0.94	2.18	21.06%
2022	15.41%	1.13	1.93	33.53%
2023	15.50%	1.02	1.76	27.94%

2024	7.26%	0.85	1.69	10.46%
2025	4.00%	0.73	1.68	4.89%

Source: Author's calculations based on Tesla, Inc. Form 10-K filings (2022–2026). Values use average assets and average equity.

The deterioration is separately measured by cash-flow indicators. Net cash provided by operating activities was positive in each of the years, but capital expenditure grew and took the free cash flow down to $4.36 billion in 2023 and $3.58 billion in 2024, from $7.57 billion in 2022. Capital expenditure declined in 2025 and free cash flow was once again positive at $6.22 billion. The company's cash-flow record also indicates that it was able to keep raising capital internally, meaning that positive cash generation does not necessarily mean there was a positive increase in accounting returns on its larger capital base.

Table 8. Cash-flow diagnostics, 2021–2025 (USD millions except ratios)

Year	Operating CF	CapEx	Free CF	OCF margin	CapEx/OCF
2021	11,497	6,482	5,015	21.36%	56.38%
2022	14,724	7,158	7,566	18.07%	48.61%
2023	13,256	8,899	4,357	13.70%	67.13%
2024	14,923	11,342	3,581	15.28%	76.00%
2025	14,747	8,527	6,220	15.55%	57.82%

Source: Author's calculations based on Tesla Form 10-K filings. Free cash flow = operating cash flow – capital expenditures.

The 2025 peer benchmark adds context that Tesla's own time series cannot provide. Tesla's net margin of 4.00% was close to BYD's 4.06%, above General Motors' 1.72%, and above Ford's −4.37%. Its ROE of 4.89%, however, was below BYD's 15.12% and slightly below General Motors' 5.12%. Tesla had the highest current ratio in the group, at 2.16, and the lowest liabilities-to-equity ratio, at 0.67. The comparison therefore portrays Tesla as relatively liquid and conservatively financed, but not as the strongest peer in shareholder returns.

Table 9. 2025 peer benchmark

Metric	Tesla	BYD	Ford	General Motors
Net margin	4.00%	4.06%	−4.37%	1.72%
ROA	2.92%	3.91%	−2.85%	1.13%
ROE	4.89%	15.12%	−20.26%	5.12%
Asset turnover	0.73	0.96	0.65	0.66
Current ratio	2.16	0.79	1.07	1.17
Liabilities/equity	0.67	2.54	7.04	3.57

Source: Author's calculations based on Tesla, BYD, Ford, and General Motors 2025 annual filings. Ratios are contextual and are not adjusted for accounting-regime or business-model differences.

The peer results should be interpreted cautiously. Ford and General Motors include large captive-finance operations, BYD reports in a different accounting environment, and the companies differ in scale and product mix. The comparison is therefore contextual rather than causal. Its main value is to prevent assessments such as "high liquidity" or "weak ROE" from being based only on Tesla's own historical range.

Table 10 uses 2022 margin and turnover relationships as arithmetic reference points for the 2025 accounting base. The exercise shows the scale of the accounting gap associated with lower margin and asset turnover, but it does not describe a realistic alternative operating history.

Maintaining the 2022 margin or turnover in 2025 would have required different combinations of prices, volumes, capacity utilization, product mix, competition, and costs. Those mechanisms are not modelled here. The resulting figures should therefore be read only as mechanical decompositions, not as forecasts, management targets, or counterfactual estimates.

Taken together, the evidence suggests three distinct phases. In 2021–2022, revenue growth, margins, asset turnover, and returns strengthened together. In 2023, reported net profitability was lifted by a material tax item even though operating margin and cash-flow efficiency had already weakened. In 2024–2025, the compression in margin and turnover became clear, while liquidity improved, liabilities-to-equity stayed low, and operating cash flow remained positive.

For managerial analysis, the results support reading indicators in pairs rather than applying isolated thresholds. Operating margin can be assessed alongside net margin, asset turnover alongside asset growth, the current ratio alongside cash generation, and liabilities-to-equity alongside ROE. This approach helps distinguish a problem of operating returns from one of short-term liquidity or financing risk.

The findings remain diagnostic rather than causal. The analysis cannot establish that recent assets are unproductive, because capital-intensive investment may require time before utilization matures. A single 2025 peer snapshot also cannot establish persistent competitive advantage. Future work should extend the same variables to a multi-year company panel, harmonize accounting classifications, add segment and market-based measures, and apply appropriate econometric tests.

Table 10. Arithmetic sensitivity illustrations for 2025

Scenario	Mechanically implied outcome
Actual 2025	Revenue $94.83bn; net income $3.79bn; ROE 4.89%
2022 asset turnover applied to 2025 average assets	Revenue ≈ $146.54bn
2022 net margin applied to actual 2025 revenue	Net income ≈ $14.62bn
2022 margin and turnover with 2025 equity multiplier	ROE ≈ 29.13%

Source: Author's calculations. These are arithmetic illustrations only; they do not model prices, capacity, product mix, competition, demand, or macroeconomic conditions.

Table 10 is therefore best used to illustrate accounting relationships. Holding selected 2022 ratios constant makes the 2025 performance gap visible, but the calculation omits the operating and market conditions that would be required to produce those ratios. It should not be interpreted as estimated "counterfactual performance."

CONCLUSIONS

The 2021-2025 analysis reveals a definite shift in Tesla's financial outlook. The performance was improved up to 2022 but operating margin and asset turnover declined after that. However, as mentioned previously, the non-cash benefit of $5.93 billion disclosed in 2023 is crucial in understanding how the transition is going, since it has lowered the diagnostic net margin to 9.37%, ROA to 9.60% and ROE to 16.89% and shows that the underlying profitability decline was more severe than implied by the net-income.

The DuPont results indicate that the decline in ROE was primarily due to lower margins and lower asset turnover, not due to higher leverage. Meanwhile, the current ratio improved and liabilities-to-equity decreased, and the operating cash flow was positive throughout the period, and free cash flow got back to approximately $6.22 billion for the year 2025. Thus, Tesla started 2025 with a relatively healthy liquidity position, but significantly lower ROCE.

The unique contribution of this paper is that it incorporates five evidence layers in the context of one reproducible firm-level case: longitudinal ratios, annual DuPont decomposition, disclosed-item earnings adjustment, cash-flow diagnostics, and external peer benchmark. The 2025 comparison also highlights the need to look at multiple metrics when assessing financial strength: Tesla's liquidity is higher than the selected peers, while its liability intensity is lower, but its ROE is lower than BYD and slightly lower than General Motors.

Draw conclusions within the scope of the design. It applies to a single company and five annual observations, and is limited in direct comparability by the differences in the accounting and business models. Future research can examine the framework with a harmonized multi-company panel, more detailed segment information, market and cash-flow valuation measures and formal econometric methods. In these boundaries the approach offers a clear cut model to evaluate the interplay between profitability, capital productivity, liquidity, cash generation and financing structure of a transition-oriented company.

AUTHOR CONTRIBUTIONS

Conceptualization, methodology, data collection, analysis, writing—original draft, and writing—review and editing: A.A.; supervision: N.N.

CONFLICTS OF INTEREST

The authors declare no conflict of interest. [Edit if a conflict exists.]

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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DATA AVAILABILITY

All Tesla financial-statement data used in this study are publicly available in the company's Form 10-K filings submitted to the U.S. Securities and Exchange Commission. Data used for the 2025 peer benchmark are publicly available in the annual filings of BYD Company Limited, Ford Motor Company, and General Motors Company. The derived ratios can be reproduced from the formulas and calculation example reported in the Materials and Methods section.

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Ecological basis for the reclamation and restoration of oil-contaminated soils in Naftalan, Azerbaijan

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ABSTRACT

Oil contamination is an important driver of soil degradation in Azerbaijan and is not limited to the Absheron Peninsula. This study evaluates the ecological conditions that constrain the natural recovery of oil-contaminated soils in the Naftalan area of western Azerbaijan and develops site-specific reclamation priorities from field observations, route-based surveys, spatial inspection, and comparative analysis. Field investigations initiated in 2024 documented contaminated patches, oil pools, vegetation responses, and areas surrounding former oil wells. The study indicates that arid conditions, strong insolation, high summer soil-surface temperatures of up to 45–50 °C, low soil moisture, and sparse vegetation reduce microbial activity and limit natural self-purification. Contamination severity was classified into four levels—low, moderate, high, and very high—and linked to progressively stronger restoration measures ranging from soil loosening and biostimulation to technical removal, bioremediation, sorption, and phytoremediation. The choice of reclamation technology should additionally account for oil composition, contamination duration, soil physicochemical and hydrophysical properties, terrain, climate, and vegetation. Tolerant herbaceous species identified as suitable candidates for biological reclamation include Anabasis aphylla, Artemisia maritima, Petrosimonia brachiata, Sorghum spp., Phragmites australis, Cynodon dactylon, and Alhagi maurorum. The findings support a staged, site-specific reclamation framework for reducing environmental risks and returning degraded land to appropriate recreational, agricultural, afforestation, or other uses.

INTRODUCTION

Oil contamination is a persistent form of land degradation in oil-producing regions because petroleum residues can alter soil structure, water–air relations, microbial activity, and the capacity of vegetation to re-establish. In Azerbaijan, research on the Absheron Peninsula has documented extensive technogenic disturbance and the long-term challenges of restoring soils affected by oil production (Ağayev & Əfkərov, 2007; İsmayılov, 2007). Oil-contaminated soils are also present outside Absheron, including the Naftalan area in western Azerbaijan, where long-term exploitation of petroleum resources has produced localized contaminated surfaces and oil-bearing depressions.

The environmental significance of this problem extends beyond visible soil degradation. Petroleum residues can impair soil porosity and moisture dynamics, reduce biological activity, and create conditions under which potentially hazardous hydrocarbon compounds persist or migrate. Earlier work has linked petroleum contamination with functional and ecological changes in soils of Azerbaijan and has emphasized the role of soil microbiota in degradation and recovery processes (Kerimov et al., 2008; Sharonova & Pakhomova, 2009). The potential mutagenic and antimutagenic properties associated with contaminated soils have also been discussed in the broader soil-microbiology literature (Skvortsova et al., 1989).

Naftalan requires a site-specific approach because its climatic conditions are comparatively dry and strongly insolated. High temperatures, low humidity, dry air, and wind exposure can accelerate surface drying and reduce the period during which soil microorganisms remain active. The special properties and historical use of Naftalan oil further distinguish the area from more intensively studied oil fields of the Absheron Peninsula (Agaeva & Mamedov, 2017). Existing Azerbaijani studies describe mechanical, biological, chemical, and combined restoration approaches for oil-contaminated land, but the suitability of any method depends on local environmental conditions and the severity of contamination (Salmanlı, 2020; Şıxbalayev, 2020).

The aim of this study is therefore to characterize the principal ecological constraints affecting the natural recovery of oil-contaminated soils in Naftalan, document the spatial and field manifestations of contamination, and develop a practical reclamation framework that links contamination severity with appropriate technical and biological restoration measures. Particular attention is given to the role of vegetation and to plant species that may support the biological stage of reclamation.

MATERIALS AND METHODS

Study area and field investigations

The study was conducted in the Naftalan area within the Ganja–Dashkasan economic region of western Azerbaijan. The investigated landscape is characterized by high summer temperatures, low atmospheric humidity, intensive insolation, and generally dry surface conditions. These factors are important because the hydrothermal regime directly influences soil moisture, microbial activity, and the rate at which petroleum residues can be naturally transformed.

Scientific field investigations were initiated in 2024 along pre-planned routes. The fieldwork focused on identifying oil-contaminated soil surfaces, describing their spatial distribution, documenting oil pools and areas surrounding old wells, and recording the condition and distribution of naturally occurring vegetation. Herbarium specimens were collected for several plant species encountered in and around contaminated sites. Route mapping and an orthophoto image were used to document the spatial context of the investigated locations (Figures 1 and 2).

Figure 1. Field routes established within the Naftalan study area.

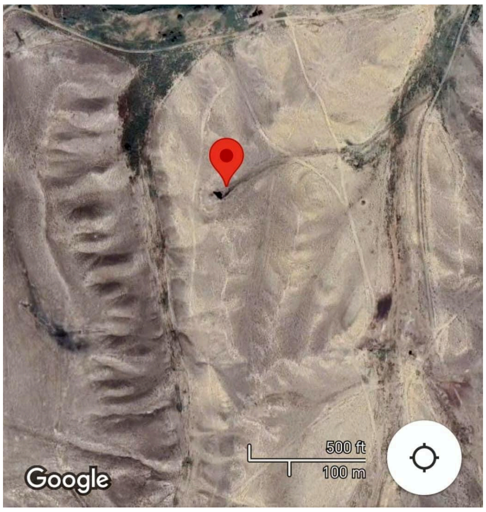

Figure 2. Orthophoto image showing the spatial context of the study area.

Analytical approach

The research combined desk-based analysis, comparative assessment, statistical generalization, and systematic interpretation of field observations. Contamination severity was classified qualitatively into four levels—low, moderate, high, and very high—using visible and physical characteristics of the soil, apparent ecological changes, vegetation response, and the type of restoration intervention considered necessary. The resulting framework was used to compare reclamation options and identify factors that should guide site-specific treatment decisions.

The study is primarily field-observational. The source materials do not report laboratory measurements of total petroleum hydrocarbons, polycyclic aromatic hydrocarbons, or microbial abundance. Accordingly, the contamination classes presented below should be interpreted as a practical field-screening framework rather than a chemical risk classification. Quantitative laboratory verification is recommended before large-scale remediation is implemented.

RESULTS AND DISCUSSION

Ecological constraints and field manifestations of contamination

The field assessment indicates that the climatic regime of Naftalan limits the natural self-purification of oil-contaminated soils. During particularly hot summer conditions, the study materials report soil-surface temperatures of approximately 45–50 °C and a decline in soil moisture of about 3–4%. Such surface heating and drying reduce the time during which microbial communities can remain active and therefore slow biological degradation of petroleum residues. Sparse vegetation further constrains soil recovery by limiting organic inputs and biological stabilization of the surface.

Vegetation cover in the contaminated landscape was generally low and was reported to reach only about 20–25% during spring and autumn in areas dominated by ephemeral plants. Trees and shrubs were largely absent from the most affected sites. These observations are consistent with the expectation that oil contamination can alter soil water–air relations and create conditions unfavorable for plant establishment. Field photographs illustrate localized vegetation stress, darkened and oil-impregnated soil surfaces, and contaminated depressions around former oil infrastructure (Figures 3 and 4).

Figure 3. Field evidence of soil and vegetation disturbance: (a) vegetation in an oil-contaminated area; (b) visibly contaminated surface soil.

Figure 4. Oil contamination near former extraction features: (a) contaminated soil around an old well; (b) an oil-filled surface depression.

Odor was detectable beyond the immediate contaminated patches during field visits, particularly under hot and windy conditions. This suggests that heating and air movement may contribute to the dispersal of volatile or semi-volatile petroleum components from exposed surfaces. The field campaign also documented active inspection and sampling around contaminated areas and old wells (Figure 5).

Figure 5. Field investigations in Naftalan: (a) inspection of contaminated soil; (b) research conducted near an old oil well and oil-bearing depression.

The composition of oil and the resident microbial community are important for selecting biological treatment options. Babayeva and Qasimova (2017) reported that strains isolated from the Naftalan oil deposit showed comparatively high activity against tested hydrocarbon substrates, whereas strains from oil-contaminated Absheron soils exhibited greater generic diversity. This finding supports the use of locally adapted microbial and plant-based approaches, while also indicating that a reclamation technology successful in one Azerbaijani oil-producing area should not automatically be transferred to another without site-specific testing.

Contamination severity and recommended restoration response

The field evidence supports a staged response in which restoration intensity increases with the apparent severity of contamination. Low-contamination sites may retain much of their ecological functionality and can initially be managed through soil loosening and measures that stimulate natural attenuation. Moderate contamination requires stronger biological support, whereas highly contaminated soils may need combined technical and biological treatment. Where the soil is heavily impregnated and free or mobile oil remains on the surface, physical removal or treatment of the most contaminated layer should precede biological reclamation (Table 1).

Table 1. Field-based contamination levels and recommended restoration response

Contamination level	Field indicators and recommended response
Low	Limited visible oil; odor may be detectable. Soil changes are minor and plant growth may be reduced. Recommended response: agrotechnical measures, soil loosening, and stimulation of natural self-purification.
Moderate	Oil is present but free oil is limited. Water–air relations, microbial activity, soil properties, seed germination, and plant development may be impaired. Recommended response: biostimulation, organic amendments, sorbents, hydrocarbon-degrading microorganisms, and phytoremediation.
High	Free oil occurs between soil particles and soil color changes markedly. Porosity and the air–water regime are strongly disrupted and vegetation becomes sparse. Recommended response: technical reclamation combined with bioremediation, sorption, biological preparations, and subsequent phytoremediation.
Very high	Soil is heavily impregnated and free or mobile oil may occur at the surface. Ecological functions and self-purification capacity are severely reduced and vegetation may be destroyed. Recommended response: remove surface oil and technically treat or remove the most contaminated soil layer, followed by biological reclamation and phytoremediation.

This graduated approach is consistent with the broader restoration literature in Azerbaijan, which emphasizes that oil-contaminated land may require mechanical, biological, chemical, thermal, or combined interventions depending on site conditions (Salmanlı, 2020; Şıxbalayev, 2020). It also avoids unnecessary technical disturbance where contamination is limited and natural or assisted biological recovery remains feasible.

Factors guiding reclamation-method selection

No single reclamation technology is appropriate for all oil-contaminated soils. The method should be selected after considering the severity and duration of contamination, oil composition, soil properties, terrain, climate, and the condition of the vegetation cover. These factors determine both the environmental effectiveness of treatment and the amount of technical intervention required (Table 2).

Table 2. Factors determining the selection of a reclamation method

Factors guiding method selection
Level of contamination with oil and petroleum products
Composition and physical characteristics of the oil
Duration of contamination
Physical and chemical properties of the soil
Hydrophysical properties and water–air regime of the soil
Landscape conditions and terrain characteristics
Climatic conditions, including heat, dryness, and wind exposure
Vegetation cover and the potential for biological recovery

In Naftalan, climatic dryness is especially important because even a technically successful removal of free oil may not immediately restore soil biological activity. Reclamation should therefore be planned as a sequence: removal or stabilization of the most mobile contamination where necessary, improvement of soil physical conditions, stimulation of biological degradation, and finally the re-establishment of vegetation. This sequence can be adjusted according to the contamination class and intended post-reclamation land use.

Plant-based biological reclamation

Vegetation is central to the biological stage of reclamation because plant cover can stabilize the soil surface, reduce erosion, influence moisture dynamics, and support microbial processes in the rhizosphere. Studies from Azerbaijan have also emphasized the value of naturally occurring vegetation in petroleum-affected environments (Əsədov et al., 2024). The present field assessment identified several tolerant herbaceous taxa that may be suitable for trial use after the most severe contamination has been reduced (Table 3).

Table 3. Recommended herbaceous plants for biological reclamation

Recommended plant taxon
Anabasis aphylla L.
Artemisia maritima L.
Petrosimonia brachiata (Pall.) Bunge
Sorghum spp.
Phragmites australis
Cynodon dactylon L.
Alhagi maurorum

These species should not be regarded as universally suitable for every contaminated patch. Their use should follow field or pilot-scale testing that evaluates establishment success, tolerance to residual petroleum, and the possibility of contaminant uptake. Annual or perennial forage grasses may be used during early biological reclamation where the contamination level and intended future land use permit. Tree and shrub establishment should be considered only after soil conditions have been sufficiently stabilized.

Environmental and economic implications

Restoring oil-contaminated soils can generate practical benefits by returning currently degraded land to productive or socially useful functions. After adequate cleaning and stabilization, suitable areas may be considered for recreation, agriculture, afforestation, landscaping, or sanitary and protective uses. The intended post-reclamation function should be defined before major intervention because it determines the acceptable residual risk, the depth of treatment, and the intensity of subsequent agrotechnical measures.

A site-specific treatment strategy may also reduce avoidable expenditure. Matching the level of technical intervention to contamination severity can prevent over-treatment of lightly affected areas while directing more intensive resources to sites with free oil or severely impaired soil functions. Early treatment may additionally reduce the risk of petroleum components migrating toward surface water or groundwater and thereby lower the likelihood of more costly restoration in the future. These are potential economic advantages rather than a formal cost–benefit result; the present study did not quantify treatment costs, land values, or monetary benefits. A dedicated economic assessment should therefore accompany any large-scale reclamation program.

CONCLUSIONS

Oil-contaminated soils in the Naftalan area occur under environmental conditions that restrict natural recovery. Strong summer heating, low moisture availability, sparse vegetation, and limited biological activity reduce the capacity of contaminated soils to self-purify. Field observations documented localized oil pools, visibly altered soils, vegetation stress, and contamination around former oil infrastructure. These conditions support the use of a staged reclamation approach rather than reliance on natural attenuation alone.

The proposed framework links four field-based contamination levels with increasingly intensive measures: soil loosening and natural-attenuation support for lightly affected soils; biostimulation, sorption, microbial treatment, and phytoremediation for moderate contamination; and combined technical and biological reclamation where contamination is high or very high. Method selection should additionally reflect oil composition, contamination history, soil properties, terrain, climate, and vegetation. Tolerant herbaceous species can support the biological stage, but their performance should be verified through pilot trials.

The principal limitation of the study is the absence of reported laboratory measurements of petroleum hydrocarbons, PAHs, microbial abundance, and treatment performance. Future research should combine the field-screening framework with quantitative soil chemistry, microbiological indicators, seasonal monitoring, and controlled remediation trials. Such evidence would allow threshold-based risk assessment and provide a stronger basis for comparing the environmental and economic efficiency of alternative reclamation technologies in Naftalan.

AUTHOR CONTRIBUTIONS

All authors contributed to the conceptualization, field investigation, analysis and interpretation of the study, and preparation of the manuscript. All authors reviewed and approved the final version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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This research received no external funding.

DATA AVAILABILITY

The field observations and supporting materials reported in this study are contained within the article, figures, and tables. Additional field materials may be available from the corresponding author on reasonable request.

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Operational value of coordinated EV charging and irrigation pumping in a PV-battery agricultural microgrid

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ABSTRACT
Agricultural microgrids increasingly combine photovoltaic generation, battery storage, irrigation pumping, and electric-vehicle charging, yet the benefit of coordinating these loads depends on the scheduling flexibility available to each service. This study examines that interaction in a PV-battery agricultural microgrid in Goranboy, Azerbaijan, using an hourly 2023 PVGIS-SARAH3 profile. Four operating cases were compared with identical hardware and service requirements: fixed EV charging and fixed irrigation (S0), flexible EV charging only (S1), flexible irrigation only (S2), and joint flexibility (S3). The modeled system included 3.991 kWp of PV and a 10.5 kWh/5.25 kW battery. Dispatch was obtained by lexicographic linear optimization under a no-export boundary. Relative to S0, S3 reduced annual grid import from 5340.029 to 4791.595 kWh (10.27%) and lowered maximum hourly-average grid import from 15.645 to 5.382 kW (65.60%). PV self-consumption increased from 47.375% to 58.766%. The individual flexibility cases showed distinct operational roles: EV scheduling contributed more to annual grid-energy reduction, whereas irrigation scheduling had the larger effect on peak demand. Simple ±20% PV and battery sensitivities preserved this qualitative pattern. For the modeled configuration, coordinated demand improved use of the existing PV-battery system without reducing the specified mobility or irrigation service.

INTRODUCTION

Distributed photovoltaic (PV) generation and battery energy storage are increasingly considered in agricultural electricity systems, where daytime solar output does not always coincide with farm demand. Because many agricultural loads can be scheduled within practical limits, system performance depends not only on installed generation and storage capacity, but also on the timing of electricity use. This has led to growing interest in water-energy coordination, battery dispatch, and supervisory control in agricultural microgrids (Brown & Göl, 2026; Mokhtare & Keysan, 2025; Safavi et al., 2025; Yadav et al., 2024).

Irrigation pumping illustrates this type of scheduling flexibility particularly well. The service requirement is the delivery of water, not electricity consumption at a particular instant. Where crop and hydraulic constraints allow some freedom in timing, pumping can be shifted within a feasible window while the required irrigation service is preserved. Previous studies have used this flexibility by coordinating irrigation with PV availability or by treating pumping as a responsive agricultural load in farm-energy and electricity-market models (García-Jiménez et al., 2026; Golmohamadi, 2021; Golmohamadi & Asadi, 2020; Mérida García et al., 2018; Navarro-González et al., 2023; Pardo & Navarro-González, 2024; Sheline et al., 2025; Wu et al., 2024).

EV charging provides a contrasting form of flexibility. The vehicle must receive a fixed amount of energy for mobility each day, but that energy does not have to be delivered at the same hours throughout the connection period. Studies of PV-assisted charging have shown that this scheduling freedom can influence self-consumption, net-load shape, and peak demand without reducing the required vehicle energy (AbuElrub et al., 2020; Fachrizal et al., 2020, 2022; Liu et al., 2023; van der Kam & van Sark, 2015; Wang et al., 2024; Wei et al., 2022).

This difference becomes important when both loads share the same local energy system. Irrigation creates a relatively large electrical demand that can be rearranged over multi-day service windows, whereas EV charging introduces a smaller demand that recurs every day. Because these forms of flexibility are often examined separately, their contributions are not directly comparable from the existing literature alone. The present analysis evaluates both within one PV-battery agricultural microgrid under the same hardware and service assumptions.

To isolate these effects, four scenarios were defined. S0 represents fixed EV charging and fixed irrigation; S1 introduces EV flexibility only; S2 introduces irrigation flexibility only; and S3 allows both loads to shift. PV capacity, battery size, mobility energy, and irrigation service remain unchanged throughout. Performance is assessed using annual grid import, maximum hourly-average grid import, PV self-consumption, and annual BESS discharge.

MATERIALS AND METHODS

Study design and scenario structure

All four scenarios were evaluated over the same hourly 2023 operating year. The PV series, battery hardware, daily EV energy requirement, and irrigation requirement were held constant; only the permitted timing of EV charging and irrigation pumping was changed. This design separates the effect of scheduling from changes in installed equipment or delivered service. The four scheduling cases are summarized in Table 1.

Table 1. Scheduling scenarios.

Scenario	Configuration and role
S0	EV fixed; irrigation fixed — baseline
S1	EV flexible; irrigation fixed — EV flexibility only
S2	EV fixed; irrigation flexible — irrigation flexibility only
S3	EV flexible; irrigation flexible — joint flexibility

PV data, local-time conversion, and sizing

The PV input was derived from the European Commission Joint Research Centre PVGIS 5.3 hourly-data tool using the PVGIS-SARAH3 database (European Commission, Joint Research Centre, 2026). The site coordinates were 40.610° N, 46.790° E, at an elevation of 158 m. PVGIS was configured for a 1 kWp crystalline-silicon system with 14% system losses, an optimum slope of 36°, and azimuth 0°. The downloaded file contained 17,520 hourly records covering 2022-2023.

PVGIS reports the hourly time field in UTC, so timestamps were converted to Azerbaijan local time (UTC+4) before the 2023 local-year series was extracted. The resulting series was checked for temporal completeness and contained 8760 hourly observations with no duplicate timestamps, missing PV values, or non-hourly gaps. Its specific yield was 1320.287020 kWh kWp−1 yr−1. With the prespecified annual PV-energy target of 5269.036111 kWh yr−1, the corresponding installed capacity was calculated as shown in Eq. (1). The full set of system and service parameters used in the model is summarized in Table 2.

$$P_{PV} = \frac{E_{PV,target}}{Y_{PV}}$$

$$\frac{5269.036111}{1320.287020} = 3.990826260641\, kWp \quad (1)$$

Table 2. System and service parameters.

Parameter	Value / rule
PV capacity	3.990826260641 kWp
Annual PV energy	5269.036111 kWh yr−1
EV energy	7.35 kWh day−1
EV availability	18:00-07:00 local time
EV maximum charging power	10.5 kW
Irrigation events	5 events yr−1
Water per event	8000 m^3 event−1
Pump power	10.9 kW
Equivalent pumping duration	88.889 full-load h event−1
Irrigation windows	I1 16-22 Jun; I2 6-12 Jul; I3 21-27 Jul; I4 5-11 Aug; I5 20-26 Aug 2023
BESS energy / power	10.5 kWh / 5.25 kW
SOC bounds	20-90% of nominal energy
Round-trip efficiency	85%
Grid export	Not allowed

EV and irrigation scheduling constraints

Daily EV demand was set at 7.35 kWh day−1, equivalent to 2682.75 kWh over the year, with charging power capped at 10.5 kW. Under the fixed schedule, charging began at 18:00. Under flexible operation, the same 7.35 kWh daily requirement could be distributed within the 18:00-07:00 connection interval. The flexibility assumption therefore changed only charging time; the modeled mobility energy remained unchanged.

Irrigation comprised five events, each delivering 8000 m^3 through a 10.9 kW pump. At rated power, one event corresponded to 88.889 equivalent full-load pumping hours. The nominal dates were 19 June (DOY 170), 9 July (190), 24 July (205), 8 August (220), and 23 August (235) 2023. Each event was assigned a seven-day window: 16-22 June, 6-12 July, 21-27 July, 5-11 August, and 20-26 August, respectively. In the fixed cases, pumping began when the relevant window opened and continued until the event requirement was completed. In the flexible cases, the same event requirement could be redistributed within that seven-day interval.

Battery model and hourly power balance

The BESS was modeled with a nominal energy capacity of 10.5 kWh and a 5.25 kW charge/discharge power limit. State of charge was constrained between 20% and 90% of nominal capacity. Round-trip efficiency was assumed to be 85%; with symmetric loss allocation, the charging and discharging efficiencies were set to $\eta c = \eta d = \sqrt{0.85} = 0.92195$. With an hourly time step, the storage balance was written as:

$$E_{t+1} = E_t + \eta_c P_{ch,t} \Delta t - \frac{P_{dis,t} \Delta t}{\eta_d} \quad (2)$$

A cyclic year-end condition, E_end = E_start, prevented the solution from drawing on unaccounted initial battery energy or ending the year with an artificial energy deficit. Grid export was not permitted. PV generation that could not be consumed directly or stored in the BESS was curtailed. The hourly power balance was enforced as:

$$P_{grid,t} + (P_{PV,t} - P_{curt,t}) + P_{dis,t} = P_{EV,t} + P_{irr,t} + P_{ch,t} \quad (3)$$

Optimization objective and performance metrics

Optimization followed a lexicographic sequence rather than a weighted single objective. Annual grid import was minimized first. Among solutions that achieved this optimum, the model then minimized maximum hourly-average grid import and, finally, annual BESS discharge throughput. The reported indicators were defined as:

$$E_{grid} = \Sigma_t P_{grid,t} \Delta t \quad (4)$$

$$P_{grid,max} = max_t (P_{grid,t}) \quad (5)$$

$$PV\ self - consumption = 100 \times [1 - \frac{E_{curt}}{E_{PV}}] \quad (6)$$

Sensitivity analysis and numerical QA

Sensitivity analysis was restricted to the jointly flexible case, S3. PV capacity was varied by −20% and +20% while the normalized 2023 hourly production profile remained unchanged. In a separate set of runs, BESS energy and power were both varied by −20% and +20%, preserving their baseline ratio. The purpose was to test whether the main operating result was sensitive to moderate changes in component size, not to carry out a new sizing optimization.

Post-optimization checks confirmed that every scenario delivered the specified annual EV and irrigation services, respected the BESS SOC limits and cyclic boundary, and satisfied the no-export condition. None of the reported solutions contained simultaneous BESS charging and discharging. Scenario and sensitivity outputs were also cross-checked against the derived percentage changes. Two schedule inputs missing from an intermediate project archive were later recovered from the original project history and are reported here: the 10.5 kW EV charging-power limit and the five seven-day irrigation windows (16-22 June, 6-12 July, 21-27 July, 5-11 August, and 20-26 August 2023). The overall modeled system configuration, scheduling structure, and reported outputs are illustrated in Figure 1.

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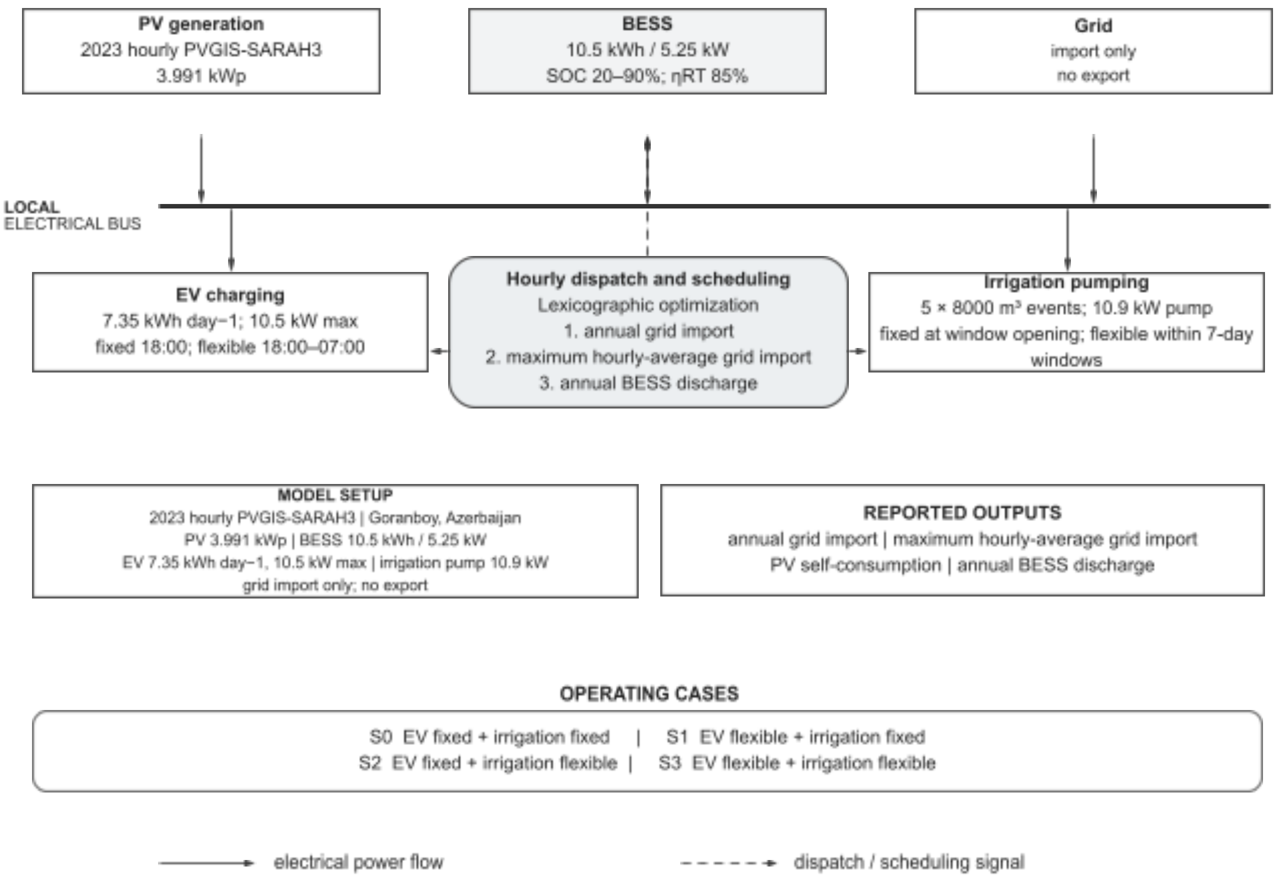

Figure 1. Schematic overview of the modeled PV-battery agricultural microgrid, scheduling cases, and reported outputs.

RESULTS AND DISCUSSION

PV resource and scenario outcomes

Using the scaled 2023 PVGIS profile, the 3.991 kWp PV array produced the prespecified 5269.036 kWh. Because PV capacity, BESS hardware, and total EV and irrigation service were identical in S0-S3, the differences reported below reflect only the scheduling of the two flexible loads. The resulting scenario outcomes are summarized in Table 3.

Table 3. Final S0-S3 operational results.

Scenario	Operational result
S0 — EV fixed + irrigation fixed	Grid 5340.029 kWh/y; peak 15.645 kW; PV self-consumption 47.375%; BESS discharge 1751.207 kWh/y
S1 — EV flexible + irrigation fixed	Grid 4932.772 kWh/y; peak 11.258 kW; PV self-consumption 56.427%; BESS discharge 2146.302 kWh/y
S2 — EV fixed + irrigation flexible	Grid 5178.200 kWh/y; peak 6.168 kW; PV self-consumption 50.167%; BESS discharge 1667.961 kWh/y
S3 — EV flexible + irrigation flexible	Grid 4791.595 kWh/y; peak 5.382 kW; PV self-consumption 58.766%; BESS discharge 2044.661 kWh/y

In the fully fixed case (S0), annual grid import was 5340.029 kWh and maximum hourly-average grid import reached 15.645 kW. PV self-consumption was 47.375%, so less than half of the available PV generation was used locally. Annual BESS discharge was 1751.207 kWh.

Allowing EV charging to shift within the overnight connection period (S1) reduced annual grid import to 4932.772 kWh, 7.63% below S0. Peak import also decreased, though less strongly, to 11.258 kW. PV self-consumption increased to 56.427%, while annual BESS discharge rose to 2146.302 kWh. In this case, the battery cycled more as the recurring EV demand was rescheduled. The improvement in PV-load matching is broadly consistent with previous smart-charging studies (AbuElrub et al., 2020; Fachrizal et al., 2020, 2022; Liu et al., 2023; van der Kam & van Sark, 2015; Wang et al., 2024; Wei et al., 2022).

Irrigation flexibility produced a different response. In S2, annual grid import decreased to 5178.200 kWh, only 3.03% below the fixed baseline, but the effect on peak demand was much larger: the annual maximum fell to 6.168 kW, a 60.57% reduction. PV self-consumption reached 50.167%, and BESS discharge decreased slightly to 1667.961 kWh. For the modeled system, shifting the 10.9 kW pump therefore mainly reduced exposure to high-demand hours rather than producing a large reduction in annual imported energy. The importance of pump scheduling as an operational degree of freedom is also emphasized in recent PV-irrigation and agricultural-microgrid studies (García-Jiménez et al., 2026; Pardo & Navarro-González, 2024; Sheline et al., 2025; Wu et al., 2024; Yadav et al., 2024).

When both forms of flexibility were available (S3), the system recorded its lowest grid import. Annual grid import fell to 4791.595 kWh yr−1, 548.434 kWh below S0, equivalent to a 10.27% reduction. Maximum hourly-average grid import was 5.382 kW, 65.60% below the baseline value. PV self-consumption increased from 47.375% to 58.766%, a gain of 11.391 percentage points, while annual BESS discharge was 2044.661 kWh yr−1.

The contrast between S1 and S2 shows that the two flexible loads provide different operational benefits. EV scheduling has the stronger effect on annual grid energy and PV utilization, whereas irrigation scheduling has the stronger effect on peak demand. S3 combines both mechanisms, but its improvement is not expected to equal the arithmetic sum of the two separate gains because a favorable PV or battery interval used by one flexible load is no longer fully available to the other. The annual grid-import comparison is shown in Figure 2.

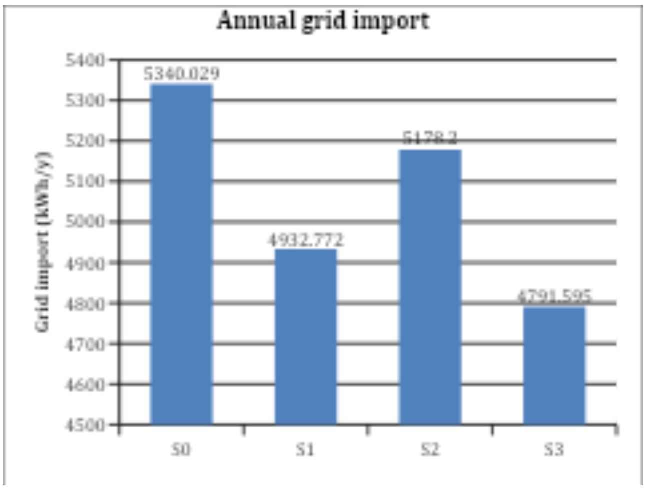

Figure 2. Annual grid import under the four scheduling scenarios.

Figure 2 summarizes the effect on annual grid energy. EV flexibility accounts for much of the reduction achieved before full coordination, while the lowest annual grid import occurs when both loads can be rescheduled. The corresponding peak-import comparison is shown in Figure 3.

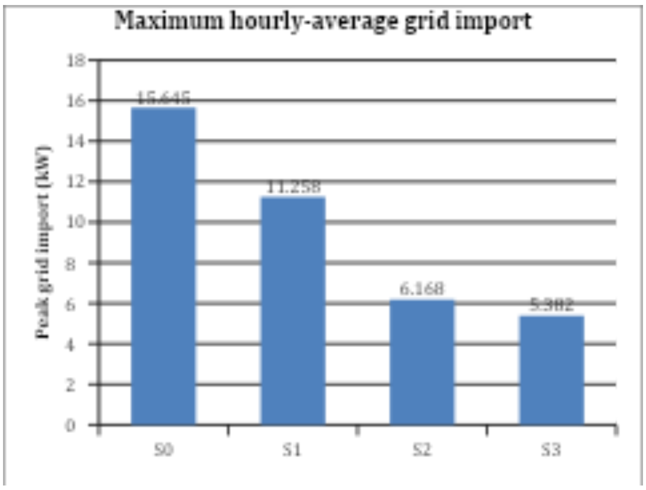

Figure 3. Maximum hourly-average grid import under the four scheduling scenarios.

The peak-demand pattern is different. Irrigation flexibility alone lowers the maximum from 15.645 to 6.168 kW, after which EV flexibility provides a smaller additional reduction to 5.382 kW in S3. Where connection capacity or peak-related network constraints are important, this distinction may be more relevant than the annual energy saving itself.

Sensitivity of S3 to PV and BESS size

Varying PV capacity produced the expected trade-off between grid import and local use of available generation. At −20% PV, annual grid import in S3 was 4990.789 kWh; at +20%, it fell to 4624.754 kWh. Over the same range, PV self-consumption decreased from 68.477% to 51.691%. These trends are not contradictory: a larger array supplied more local energy and reduced imports, but the no-export boundary also caused a larger share of the additional generation to be curtailed.

Battery sizing showed a different response. Reducing both BESS energy and power by 20% increased S3 grid import to 5165.613 kWh and lowered PV self-consumption to 50.415%. Increasing both ratings by 20% reduced grid import to 4656.892 kWh and raised self-consumption to 61.774%. The improvement above the baseline BESS size was smaller than the deterioration below it, which is consistent with diminishing marginal value from additional storage around the selected configuration.

Despite these changes in annual energy performance, the S3 peak remained within a narrow range of approximately 5.26 to 5.50 kW across all six sensitivity runs. This relative stability indicates that, within the present model, the large reduction from S0 to S3 is driven mainly by load scheduling rather than by moderate PV or BESS resizing. The six sensitivity cases are summarized in Table 4, and their annual grid-import values are shown in Figure 4.

Table 4. Simple S3 sensitivity to PV and BESS size.

Sensitivity case	Operational result
PV −20% — 3.193 kWp	Grid 4990.789 kWh/y; peak 5.503 kW; PV self-consumption 68.477%; BESS discharge 1983.654 kWh/y
PV baseline — 3.991 kWp	Grid 4791.595 kWh/y; peak 5.382 kW; PV self-consumption 58.766%; BESS discharge 2044.661 kWh/y
PV +20% — 4.789 kWp	Grid 4624.754 kWh/y; peak 5.260 kW; PV self-consumption 51.691%; BESS discharge 2073.314 kWh/y
BESS −20% — 8.4 kWh / 4.2 kW	Grid 5165.613 kWh/y; peak 5.390 kW; PV self-consumption 50.415%; BESS discharge 1670.643 kWh/y
BESS baseline — 10.5 kWh / 5.25 kW	Grid 4791.595 kWh/y; peak 5.382 kW; PV self-consumption 58.766%; BESS discharge 2044.661 kWh/y
BESS +20% — 12.6 kWh / 6.3 kW	Grid 4656.892 kWh/y; peak 5.374 kW; PV self-consumption 61.774%; BESS discharge 2179.364 kWh/y

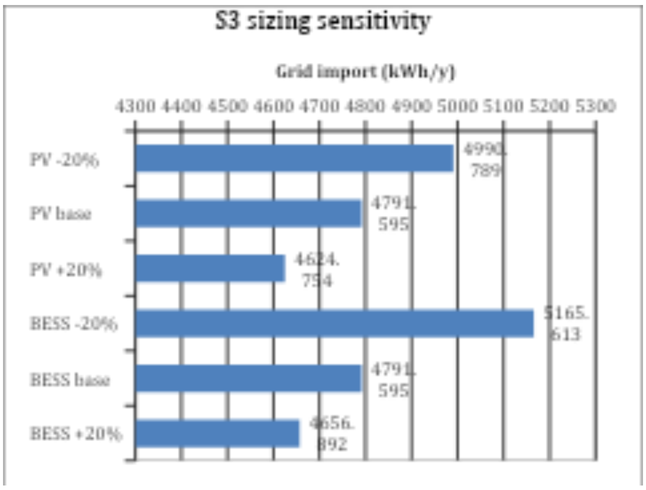

Figure 4. S3 annual grid import under the simple PV and BESS sensitivity cases.

Scope and limitations

The analysis is deliberately limited to operating strategies for one specified PV-battery system and does not seek an economically or technically optimal system size. PV and BESS capacities are fixed in the core S0-S3 comparison, while the ±20% sensitivity cases are used only to test whether the main conclusions are sensitive to moderate changes in component size.

Several factors that could affect real-world dispatch were kept outside the model. The study uses a single 2023 PV profile and does not represent forecast error, battery degradation, dynamic electricity tariffs, or revenue from electricity export. Including these elements could alter the preferred dispatch and would require a broader model than the four-scenario operational comparison considered here.

For reproducibility, two schedule-level inputs that were absent from an intermediate archive were checked against the original project history before the manuscript was finalized. The EV charging-power limit was 10.5 kW, and the irrigation windows were 16-22 June, 6-12 July, 21-27 July, 5-11 August, and 20-26 August 2023. These are the values used in the completed numerical run.

CONCLUSIONS

The modeled system achieved substantial operational gains without any change in installed PV-battery hardware or reduction in mobility and irrigation service. With both loads flexible, annual grid import decreased from 5340.029 kWh in S0 to 4791.595 kWh in S3, a 10.27% reduction. Over the same comparison, maximum hourly-average grid import fell from 15.645 to 5.382 kW (65.60%), while PV self-consumption increased from 47.375% to 58.766%.

The individual flexibility cases explain the combined result. Shifting the EV load had the greater influence on annual grid energy and PV utilization, whereas shifting the irrigation load had the greater influence on peak demand. These are distinct operational benefits, and their combination accounts for the performance of the jointly flexible case in the configuration examined.

The limited sizing sensitivities did not change this interpretation. Additional PV reduced grid imports but also increased the fraction of generation that could not be absorbed locally, whereas additional storage improved PV utilization with a smaller marginal benefit above the baseline size. Peak grid import in S3 remained comparatively stable across the ±20% cases, supporting the conclusion that scheduling was the main driver of peak reduction in this model.

For this case study, demand flexibility can therefore be regarded as an operational resource rather than merely as a complement to larger PV or battery capacity. It did not eliminate the need for grid electricity, but it allowed the same local generation and storage assets to be used more effectively while preserving the specified EV and irrigation services.

AUTHOR CONTRIBUTIONS

Conceptualization, methodology, data curation, formal analysis, interpretation of results, and manuscript preparation were carried out collaboratively, with responsibilities distributed among the four authors. All authors contributed to reviewing and editing the manuscript and approved the final version.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

FUNDING

This research received no external funding.

DATA AVAILABILITY

The hourly PV series was obtained from the openly accessible European Commission Joint Research Centre PVGIS service. The retained study archive includes the original PVGIS CSV, the processed 2023 Azerbaijan-time PV series, and the numerical audit workbook. The scheduling parameters used for the reported runs are documented in the manuscript and audit package. These materials can be supplied as supplementary files or provided by the corresponding author.

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Dietary exposure to mycotoxins and their pharmacological and toxicological consequences: a systematic review

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ABSTRACT

Mycotoxins are toxic compounds that some filamentous fungi produce and that can contaminate foods such as cereals, nuts, oilseeds, dried fruits, and processed plant products. People can ingest these toxins regularly without realizing it because contaminated food may look, smell, and taste normal. This systematic review and meta-analysis evaluated how dietary mycotoxin exposure affects human health, focusing on aflatoxins, ochratoxin A, fumonisins, trichothecenes, zearalenone, and patulin. It examined their main dietary sources, how the body absorbs and processes them, their biological targets, and their toxic effects. The evidence shows that mycotoxins can damage several body systems. The severity of the effects depends on the specific toxin, dose, duration of exposure, and individual susceptibility. Aflatoxins showed the strongest links to liver injury, DNA damage, and hepatocellular carcinoma. Ochratoxin A mainly affected the kidneys, while fumonisins were associated with liver damage and developmental toxicity. Trichothecenes primarily caused gastrointestinal, immune, and blood-related problems. Zearalenone acted like estrogen and affected reproductive health. Patulin mainly caused gastrointestinal and systemic toxicity. For example, a person who regularly eats food contaminated with aflatoxin may develop liver damage over time and face a higher risk of liver cancer, even if the food shows no visible mold. Similarly, repeated exposure to ochratoxin A may gradually impair kidney function. Eating foods contaminated with several mycotoxins at the same time makes the risk harder to predict because the toxins may interact and increase or alter each other's effects. Overall, dietary exposure to mycotoxins remains a significant food-safety and public-health problem. These toxins can disrupt cells and molecular processes and, with prolonged exposure, contribute to serious organ damage and chronic disease. We need stronger monitoring of food products, better farming and storage practices, more accurate exposure assessment, and effective prevention strategies. We also need more long-term studies in humans to determine how combined exposure to multiple mycotoxins affects health and to improve food-safety policies.

INTRODUCTION

The sustainability of modern food systems depends not only on increasing agricultural production but also on maintaining food safety, resource efficiency, economic viability, and resilience throughout the supply chain. Food losses arising from biological contamination can reduce the value and usability of agricultural commodities while also wasting the land, water, energy, labour, and other inputs invested in their production. Consequently, food-safety hazards that reduce the quantity or quality of marketable food should also be considered within the broader context of sustainable resource management. Mycotoxin contamination is particularly relevant to this perspective because these toxic metabolites can occur in agricultural commodities without necessarily producing visible changes in the appearance or sensory quality of contaminated products (WHO, 2023; Gage et al., 2024).

Mycotoxins are naturally occurring secondary metabolites produced by several genera of filamentous fungi, particularly Aspergillus, Fusarium, Penicillium, and related toxigenic species. They can contaminate crops before harvest and may continue to develop or persist during drying, storage, transportation, processing, and distribution. Cereals, maize, rice, oilseeds, nuts, dried fruits, spices, and other plant-derived commodities are among the food products commonly affected. The occurrence and concentration of mycotoxins are influenced by fungal species, crop characteristics, temperature, precipitation, relative humidity, drought stress, insect damage, agricultural practices, harvesting conditions, and post-harvest management (WHO, 2023; Liu & Van der Fels-Klerx, 2021). Because these factors operate at different stages of production and distribution, mycotoxin contamination represents a multistage risk that extends beyond conventional end-product food-safety control.

The public-health importance of mycotoxins provides the primary justification for their control. Different mycotoxins have distinct toxicological profiles and may affect the liver, kidneys, gastrointestinal system, immune system, endocrine system, and reproductive or developmental processes. Aflatoxins are of particular concern because aflatoxin B1 is a potent carcinogenic and genotoxic compound. The International Agency for Research on Cancer has classified naturally occurring aflatoxins as carcinogenic to humans, while the Joint FAO/WHO Expert Committee on Food Additives has identified chronic hepatitis B virus infection as an important factor influencing aflatoxin-related liver-cancer risk (IARC, 2012; JECFA, 2016). Other important foodborne mycotoxins include ochratoxin A, fumonisins, zearalenone, deoxynivalenol, nivalenol, T-2 and HT-2 toxins, and patulin, which have been associated with different adverse health effects in humans and animals (WHO, 2023; Alvito et al., 2022).

The consequences of contamination, however, are not limited to human and animal health. When agricultural commodities exceed safety requirements, their economic value may be reduced through rejection, downgrading, restricted use, additional processing, or disposal. Such outcomes represent not only direct financial losses for producers and other supply-chain actors but also an inefficient use of the resources embodied in the production of the affected commodities. Recent research has increasingly recognized the relationship between mycotoxin contamination, food security, financial losses, trade, and the sustainability of food production systems (Akpoghelie et al., 2025). More broadly, reducing food loss and waste can improve the environmental and economic efficiency of food supply chains by avoiding the unnecessary use of resources and reducing the environmental burden associated with producing food that is ultimately not consumed (Gage et al., 2024).

From a green-economy perspective, this relationship creates an important management problem. Resources must be allocated among preventive agricultural practices, monitoring, analytical testing, drying and storage infrastructure, processing, quality assurance, and other control measures. These interventions themselves require financial, technological, and material resources. Therefore, the objective of mycotoxin management should not be defined exclusively as achieving the lowest possible contamination level regardless of cost. A more integrated approach considers how preventive measures can reduce health risks and food losses while using economic and environmental resources efficiently. This perspective places mycotoxin management within the broader framework of sustainable production and resource-efficient food systems.

Climate change adds another layer of complexity to this problem. Changes in temperature, precipitation, relative humidity, drought frequency, and other environmental conditions can influence fungal growth, crop susceptibility, insect pressure, and mycotoxin formation. Quantitative modelling studies indicate that climate-related changes may modify mycotoxin occurrence in cereal crops, although the magnitude and direction of these effects vary according to crop, region, fungal species, and environmental conditions (Liu & Van der Fels-Klerx, 2021). More recent risk-assessment research has emphasized the need to integrate climate information with predictive models and food-safety risk assessment to anticipate changes in mycotoxin exposure along the food and feed chain (Assunção et al., 2022). Consequently, climate adaptation and mycotoxin prevention increasingly need to be considered together rather than as separate agricultural and food-safety issues.

The importance of climate-sensitive surveillance is also reflected in recent studies of mycotoxin occurrence. Evidence from different agricultural regions indicates that changing climatic conditions may influence the distribution of toxigenic fungi and the occurrence of both established and emerging mycotoxins. Recent reviews have therefore emphasized the importance of strengthening analytical capacity, surveillance systems, and early-warning approaches while improving understanding of the relationship between environmental conditions and mycotoxin occurrence (Foerster et al., 2024). Such approaches may allow interventions to be implemented earlier in the production chain, potentially reducing the need for costly corrective measures after commodities have already become contaminated.

Another important consideration is the limited effectiveness of relying exclusively on processing or end-product testing. Many mycotoxins are chemically stable and can survive conventional food-processing operations, meaning that contamination detected at a later stage may be difficult to remove completely (WHO, 2023). Consequently, prevention through appropriate agricultural practices, rapid drying, moisture control, storage management, monitoring, and targeted intervention can be more compatible with resource-efficient food production than relying primarily on the rejection or disposal of contaminated products. Recent reviews have consequently emphasized integrated prevention and mitigation strategies extending from pre-harvest management to post-harvest control and analytical detection (Mohan et al., 2024).

Despite extensive research on mycotoxin occurrence, analytical detection, toxicology, exposure assessment, and regulatory limits, an interdisciplinary gap remains between mycotoxin risk management and the broader economic and environmental performance of food systems. Climate-related risk modelling has advanced considerably, while research on food loss and sustainability has demonstrated the importance of improving resource efficiency throughout food supply chains. At the same time, recent literature has highlighted the substantial economic consequences associated with mycotoxin contamination (Liu & Van der Fels-Klerx, 2021; Assunção et al., 2022; Akpoghelie et al., 2025). However, these dimensions are not always integrated into a common decision-making framework in which health protection, environmental impacts, food losses, prevention costs, and resource allocation are evaluated simultaneously.

This gap is particularly relevant to green-economy research because mycotoxin control can be formulated as a resource-allocation and optimization problem. Producers, processors, regulators, and other supply-chain actors must determine where and when limited resources should be invested to obtain the greatest reduction in contamination and associated losses. Possible decisions include selecting appropriate crop-management practices, improving drying and storage conditions, determining sampling and testing frequency, prioritizing high-risk commodities or locations, and deciding whether contaminated products should be processed, redirected to alternative uses, or discarded. The economic and environmental implications of these decisions may differ substantially, making risk-based prioritization an important component of sustainable food-system management.

An integrated framework could therefore connect mycotoxin surveillance with environmental indicators, food-loss measurements, production costs, contamination probabilities, and health-risk estimates. Predictive models and early-warning systems could support identification of high-risk periods and locations, while economic analysis could help determine whether preventive interventions justify their costs. Such an approach would move mycotoxin management from a predominantly reactive food-safety model toward a preventive and resource-efficient system in which interventions are prioritized according to risk, expected effectiveness, and economic and environmental consequences.

Against this background, the present study examines mycotoxin contamination as an interdisciplinary food-system risk and considers its implications for sustainable agricultural production, resource efficiency, food-loss reduction, and economic decision-making. Particular attention is given to the principal groups of foodborne mycotoxins, their agricultural sources and toxicological significance, the environmental and management factors influencing their occurrence, and the potential role of preventive, predictive, and optimized control strategies. By connecting food safety with environmental sustainability and economic resource allocation, this study aims to contribute to an integrated framework for managing mycotoxin risks within resilient and resource-efficient food systems.

METHODOLOGY

This systematic review and meta-analysis followed the PRISMA 2020 guidelines. To define the eligibility criteria and structure the literature search, the PICOS framework (Population, Intervention/Exposure, Comparator, Outcomes, and Study Design) was applied.

The literature search covered PubMed, Web of Science Core Collection, and Scopus, including studies published from January 2000 to June 2026. Search terms were combined using Boolean operators (AND/OR) and included "mycotoxins," "aflatoxins," "ochratoxin A," "fumonisins," "deoxynivalenol," "zearalenone," "T-2 toxin," "patulin," "dietary exposure," "foodborne exposure," "human health," "toxicity," "toxicological effects," "pharmacokinetics," and "biomarkers." Relevant reference lists were also checked to identify additional eligible studies. Duplicate records were removed before screening.

The PICOS criteria were defined as follows: Population (P) included humans of any age or sex exposed to mycotoxins through food or dietary intake; Exposure (I/E) referred to dietary exposure to individual or multiple mycotoxins, assessed through food contamination data, dietary intake estimates, or validated biomarkers; Comparator (C) included unexposed, lower-exposure, or control groups; Outcomes (O) covered toxicological and health effects, including hepatotoxicity, nephrotoxicity, carcinogenicity, genotoxicity, immunotoxicity, endocrine and reproductive effects, neurotoxicity, oxidative stress, and relevant biomarkers; and Study design (S) included cohort, case-control, cross-sectional, population-based, and human biomonitoring studies.

Eligible studies involved human participants, assessed foodborne mycotoxin exposure, and reported relevant health or toxicological outcomes. For inclusion in the meta-analysis, studies also needed to provide sufficient quantitative information, such as ORs, RRs, HRs, mean differences, or 95% confidence intervals. Conference abstracts, editorials, reviews without original data, duplicate publications, and studies that did not report relevant outcomes were excluded. Animal and in-vitro studies were also excluded from the primary quantitative synthesis, although experimental evidence was considered separately to help explain possible toxicological mechanisms.

During screening, titles and abstracts were assessed first, followed by full-text evaluation of potentially eligible studies. Two reviewers independently performed study selection and data extraction, while disagreements were resolved through discussion or consultation with a third reviewer. The extracted information included study characteristics, population size, mycotoxin type, exposure level, analytical or biomonitoring methods, reported outcomes, effect estimates, and potential confounders.

Study quality was then assessed using validated tools appropriate to each study design, including the Newcastle–Ottawa Scale for cohort and case-control studies. Where sufficient comparable data were available, random-effects meta-analysis was performed. Heterogeneity was evaluated using Cochran's Q and I^2 statistics, and subgroup or sensitivity analyses were conducted where appropriate. Finally, publication bias was assessed using funnel plots and Egger's test when the number of included studies was sufficient.

DIETARY SOURCES AND EXPOSURE PATHWAYS OF MYCOTOXINS

Mycotoxins are secondary metabolites produced predominantly by filamentous fungi belonging to genera such as Aspergillus, Fusarium, Penicillium, Alternaria and Claviceps. Their entry into the food chain is closely associated with contamination of agricultural commodities before harvest, during harvesting, storage and processing. Cereals and cereal-derived foods represent particularly important dietary sources, although mycotoxins may also occur in nuts, dried fruits, spices, beverages and foods of animal origin. The persistence of several mycotoxins during food processing means that contamination at an earlier stage of the food chain may ultimately become a source of human dietary exposure (Bennett & Klich, 2003; Eskola et al., 2020; EFSA, 2026).

Mycotoxins are naturally occurring secondary metabolites produced by a limited number of filamentous fungi, particularly species belonging to the genera Aspergillus, Penicillium and Fusarium. They are important food-chain contaminants because toxin-producing fungi can colonise crops before harvest and continue to produce or maintain mycotoxins during harvesting, processing and storage. Cereals, nuts, oilseeds, spices, dried fruits, apples, coffee and products derived from contaminated raw materials are among the principal dietary sources of exposure (Marín et al., 2013; Wu et al., 2014). The occurrence of mycotoxins is strongly influenced by environmental and technological conditions, with elevated temperature, moisture, drought stress, insect damage and inadequate post-harvest storage contributing to fungal growth and toxin formation. Consequently, dietary exposure should be considered a dynamic process extending across the entire food-production chain rather than a contamination event restricted to the primary crop.

The toxicological importance of mycotoxins arises from the combination of their widespread occurrence, chemical diversity, persistence and biological activity. Several hundred mycotoxins have been identified, although a smaller group—including aflatoxins, ochratoxin A (OTA), patulin, fumonisins, zearalenone (ZEN), deoxynivalenol (DON), nivalenol (NIV), and T-2 and HT-2 toxins—accounts for much of the concern associated with human dietary exposure (WHO, 2023; Marín et al., 2013). Importantly, contamination is not always restricted to a single toxin. Co-occurrence of several mycotoxins within the same food or dietary pattern is frequently reported, raising the possibility of additive, synergistic or antagonistic interactions that may not be adequately represented by risk assessments based on individual compounds (Grenier & Oswald, 2011; Smith et al., 2016). This issue is particularly relevant to a systematic assessment of dietary exposure because the toxicological consequences of mixtures may differ from those predicted from exposure to individual mycotoxins.

Dietary exposure occurs through both direct and indirect pathways. Direct exposure results from consumption of contaminated plant-derived foods, whereas indirect exposure can occur when food-producing animals consume contaminated feed and subsequently transfer mycotoxins or their metabolites into edible animal products. A well-characterised example is the conversion of aflatoxin B1 (AFB1) in animal tissues into aflatoxin M1 (AFM1), which can subsequently be detected in milk. The magnitude of this carry-over is influenced by factors such as AFB1 intake, milk production, animal variability and feeding conditions (Pettersson, 2023). Thus, the food-exposure pathway extends beyond the original contaminated crop and may include feed, livestock metabolism, animal-derived foods and subsequent human consumption.

Among foodborne mycotoxins, aflatoxins have received particular attention because of their high potency and well-established hepatotoxic and carcinogenic properties. AFB1 is primarily produced by Aspergillus flavus and A. parasiticus and may contaminate maize, sorghum, rice, oilseeds, peanuts, tree nuts and several spices. After ingestion, AFB1 undergoes hepatic bioactivation, principally through cytochrome P450 enzymes, generating the highly reactive AFB1-8,9-epoxide. This metabolite can form adducts with DNA and proteins and is central to the molecular mechanisms underlying hepatotoxicity and hepatocarcinogenesis (Wu et al., 2014). JECFA has classified aflatoxins among the most potent naturally occurring mutagenic and carcinogenic substances, while epidemiological evidence demonstrates a particularly important association between aflatoxin exposure, hepatitis B virus infection and liver cancer risk (JECFA, 2016). The toxicological significance of AFB1 therefore extends from acute hepatic injury at high exposure levels to chronic genotoxic and carcinogenic effects under sustained exposure.

The dietary fate of aflatoxins also illustrates the importance of metabolism in determining internal exposure. Following absorption, AFB1 can undergo competing pathways of bioactivation, detoxification and conjugation. Its metabolites can subsequently be detected in biological matrices and used as biomarkers of exposure. In food-producing animals, hepatic metabolism can also generate AFM1, which may subsequently be excreted into milk. Consequently, the concentration measured in a food commodity does not necessarily correspond directly to the biologically active dose received by the consumer. The distinction between external dietary exposure and internal exposure is therefore essential when interpreting toxicological evidence.

Ochratoxin A is another important foodborne mycotoxin, produced by several species of Aspergillus and Penicillium. It has been detected in cereals and cereal products, coffee, dried vine fruits, wine, grape juice, spices and other commodities. Dietary exposure to OTA has attracted particular attention because of its nephrotoxicity and potential effects on immune and developmental processes (Marín et al., 2013; WHO, 2023). Experimental evidence provides strong support for renal toxicity in animals, whereas the interpretation of its carcinogenic potential in humans remains more uncertain. This distinction is important in systematic reviews because evidence from experimental models should not automatically be treated as equivalent to evidence of an established human health effect. The biological activity of OTA nevertheless makes chronic dietary exposure an important area of food-safety assessment.

Patulin represents a somewhat different exposure pattern because its principal dietary source is associated with damaged or mouldy fruits, particularly apples and apple-derived products. It is produced by several fungal genera, including Penicillium, Aspergillus and Byssochlamys, and can therefore enter the human diet through contaminated fruit and fruit products. Experimental studies have demonstrated gastrointestinal, hepatic, renal and immunological effects, while genotoxic activity has also been reported. However, evidence for carcinogenicity in humans remains insufficient (WHO, 2023). The occurrence of patulin consequently illustrates the importance of considering both the prevalence of contamination and the toxicological characteristics of individual mycotoxins when estimating population-level dietary risk.

Fusarium-derived mycotoxins constitute another major group of dietary contaminants. Fusarium species commonly colonise cereal crops and produce structurally and biologically diverse toxins, including trichothecenes such as DON, NIV, T-2 and HT-2 toxins, as well as ZEN and fumonisins. Their distribution is partly commodity-specific: DON and ZEN are frequently associated with wheat and other cereals, T-2 and HT-2 toxins are important contaminants of oats and other grains, whereas fumonisins are particularly associated with maize (WHO, 2023; Marín et al., 2013). However, geographical, climatic, agricultural and storage conditions can substantially alter these patterns.

DON and related trichothecenes primarily exert their effects through disruption of ribosomal function and protein synthesis, with subsequent activation of cellular stress and inflammatory pathways. Acute exposure may produce gastrointestinal disturbances, reduced food intake and vomiting, whereas repeated exposure has been associated particularly with immunotoxic and growth-related effects in experimental models (Wu et al., 2014). The biological activity of DON therefore extends beyond conventional acute toxicity and includes effects on cellular signalling, immune responses and gastrointestinal function. Such mechanisms are relevant to the pharmacological dimension of mycotoxin research because some effects occur at molecular targets that also participate in normal physiological signalling pathways.

ZEN differs mechanistically from the trichothecenes because of its pronounced estrogenic activity. Its structural similarity to endogenous estrogens allows interaction with estrogen receptors and may result in reproductive and endocrine effects. Metabolism of ZEN generates α- and β-zearalenol, metabolites with different estrogenic potencies, meaning that toxicological evaluation should consider both the parent compound and its biotransformation products (Zinedine et al., 2007). Experimental evidence indicates particularly pronounced reproductive effects in pigs, while the relevance and magnitude of these effects in humans depend on exposure level, metabolism and individual susceptibility. From a dietary-exposure perspective, ZEN therefore provides an important example of how metabolic transformation can modify the biological activity of a mycotoxin.

Fumonisins, particularly fumonisin B1 (FB1), are predominantly associated with maize and maize-based products. Their principal molecular target is ceramide synthase, and disruption of sphingolipid metabolism contributes to their cellular and tissue toxicity. Experimental studies have demonstrated hepatotoxic and nephrotoxic effects, while epidemiological investigations have raised concerns regarding associations between fumonisin exposure and oesophageal cancer and neural tube defects. However, causal interpretation in human populations requires careful consideration of co-exposures, nutritional status and other environmental determinants (Wu et al., 2014). The simultaneous occurrence of fumonisins and aflatoxins is of particular interest because both may contaminate cereals and cereal-based foods, and JECFA has identified experimental evidence suggesting potentially additive or synergistic effects, while noting that comparable evidence in humans remains limited (JECFA, 2016).

An important characteristic of dietary mycotoxin exposure is therefore that the toxicological outcome cannot always be predicted from the concentration of a single toxin in a single food. Exposure is influenced by food consumption patterns, portion size, frequency of consumption, processing, geographical origin, age, body weight, nutritional status, metabolism and the simultaneous presence of other contaminants. Total-diet studies and biomonitoring approaches are consequently valuable complements to occurrence data because they allow estimation of actual or integrated exposure rather than relying solely on concentrations measured in individual commodities (Marín et al., 2013). Biomarkers may further provide evidence of internal exposure and can help bridge the gap between dietary intake and biologically effective dose.

The toxicological consequences of mycotoxin exposure span multiple biological systems. Depending on the compound and exposure scenario, reported effects include hepatotoxicity, nephrotoxicity, gastrointestinal injury, immunotoxicity, reproductive and endocrine disruption, developmental toxicity, oxidative stress, genotoxicity and carcinogenesis (Wu et al., 2014; Marín et al., 2013). These outcomes are mediated through diverse molecular mechanisms, including oxidative damage, inhibition of protein synthesis, interference with lipid and sphingolipid metabolism, DNA adduct formation, mitochondrial dysfunction, inflammatory signalling and modulation of nuclear receptors. Such mechanistic diversity explains why the health consequences of mycotoxins cannot be reduced to a single toxicological endpoint.

The pharmacological dimension of mycotoxin exposure is also increasingly relevant. Mycotoxins and their metabolites may interact with metabolic enzymes, transport proteins, nuclear receptors, cellular signalling pathways and drug-metabolising systems. These interactions raise the possibility that chronic dietary exposure could modify the biological response to simultaneously administered pharmaceuticals or other xenobiotics. Conversely, medications or nutritional compounds may influence mycotoxin metabolism and toxicity. The available evidence remains heterogeneous, and the clinical significance of many reported interactions has not yet been established; nevertheless, this area provides an important bridge between conventional food toxicology and pharmacological risk assessment.

Dietary mycotoxin exposure should be conceptualised as a multidimensional process connecting environmental contamination, agricultural production, food and feed chains, processing, animal metabolism, human dietary intake, absorption, biotransformation and biological effects. The distinction between external exposure, internal dose and toxicological outcome is particularly important because parent mycotoxins may be metabolically activated or detoxified after ingestion, while some metabolites may possess biological activities that differ substantially from those of the parent compound. A systematic review of dietary mycotoxins should therefore integrate occurrence data with exposure estimates, toxicokinetic and metabolic evidence, biomarkers, molecular mechanisms and documented health outcomes. Such an integrated approach provides a more biologically meaningful framework for evaluating the pharmacological and toxicological consequences of mycotoxin exposure across the food-exposure network.

Table 1. Major foodborne mycotoxins: principal dietary sources, mechanisms of toxicity, and associated health effects.

Major dietary sources	Principal pharmacological/toxicological mechanisms	Major clinical and toxicological consequences
Peanuts/ground nuts, maize, tree nuts, oilseeds, cereals; AFM_1 may occur in milk and dairy products following carry-over of AFB_1 from contaminated animal feed.	AFB_1 undergoes metabolic bioactivation to a reactive epoxide that forms DNA adducts, producing genotoxicity and mutations. Molecular mechanisms include disruption of DNA integrity and altered expression of genes involved in carcinogenesis, including TP53.	Hepatocellular carcinoma, acute aflatoxicosis and severe hepatic injury; chronic exposure is also associated with impaired growth and immune effects. Aflatoxins are established genotoxic and carcinogenic hazards.
Cereals and cereal products (e.g., wheat and barley), coffee, dried fruits, wine and grape products, spices and other plant-derived foods.	Multiple mechanisms have been proposed, including inhibition of protein synthesis, oxidative stress, mitochondrial dysfunction and interference with cellular signaling. Genotoxic mechanisms, including DNA damage, have also been investigated.	Predominantly nephrotoxicity, including renal tubular injury; effects on fetal development and the immune system have been reported. Renal carcinogenicity is well established in experimental animals, whereas the extent of the human carcinogenic risk remains subject to scientific assessment.
Maize, wheat, barley, oats and other cereals contaminated with Fusarium spp.	Structural similarity to 17β-estradiol allows ZEN and its metabolites to interact with estrogen receptors (ERα and ERβ), producing estrogenic activity and endocrine disruption.	Reproductive and endocrine toxicity, including estrogenic effects, altered reproductive function and impaired fertility at sufficiently high exposures. Effects are particularly well documented in experimental animals and livestock.
Mainly maize (corn) and maize-derived products.	Potent inhibition of ceramide synthase disrupts de novo sphingolipid biosynthesis, leading to altered sphingolipid homeostasis, membrane function and cell signaling.	Hepatotoxicity and nephrotoxicity in experimental systems; epidemiological evidence has associated fumonisin exposure with oesophageal cancer in humans. Prenatal exposure has also been investigated in relation to neural tube defects.
Wheat, barley, oats, rye and other cereal grains. DON is particularly associated with wheat and other cereals, whereas T-2/HT-2 toxins are important contaminants of oats and other grains.	DON binds to the 60S ribosomal subunit and induces a characteristic ribotoxic stress response, involving activation of MAPK signaling pathways. T-2 toxin causes profound inhibition of protein synthesis and cellular injury, particularly in rapidly dividing tissues.	Gastrointestinal toxicity, including nausea, vomiting, diarrhea, abdominal discomfort and anorexia. Experimental and occupational evidence also indicates immunotoxicity; severe exposure to T-2 toxin can produce mucosal and hematological injury.
Rotten or mould-damaged apples, apple juice and apple-derived products; may also occur in other mouldy fruits.	Reacts with sulfhydryl (–SH) groups in proteins and cellular antioxidants such as glutathione, contributing to oxidative stress and cellular dysfunction.	Gastrointestinal disturbances, including nausea and vomiting; experimental studies demonstrate hepatic, renal and immunotoxic effects. Patulin is considered genotoxic, although a carcinogenic effect in humans has not been demonstrated.

Sources: The table synthesizes information from the World Health Organization (WHO), the European Food Safety Authority (EFSA), and the International Agency for Research on Cancer (IARC), with mechanisms and health endpoints cross-checked against their current assessments.

The food chain is therefore only part of the picture. From a food-safety perspective, exposure does not necessarily result from direct consumption of a contaminated plant commodity. Mycotoxins may move through interconnected plant–animal–human pathways. Humans may therefore be exposed directly by consuming contaminated cereals, nuts, fruits and other plant-derived foods, or indirectly through animal products obtained from livestock consuming contaminated feed. This creates a dietary exposure continuum in which fungal contamination, agricultural practices, feed composition, animal metabolism, food processing and human consumption are interconnected determinants of the final internal dose (Wu et al., 2014; Adebo et al., 2022).

The indirect pathway is particularly relevant for compounds capable of undergoing metabolic conversion and carry-over into edible animal products. A well-characterized example is aflatoxin B_1 (AFB_1). Following ingestion of contaminated feed by dairy cattle, AFB_1 is metabolized primarily in the liver, with aflatoxin M_1 (AFM_1) subsequently excreted into milk. Consequently, contamination of feed may result in secondary contamination of milk and dairy products intended for human consumption. Reported AFB_1-to-AFM_1 carry-over varies considerably according to feed intake, milk yield, animal physiology and other production conditions; reviews generally indicate an average transfer of approximately 1–2%, although higher values have been reported under particular circumstances (Pettersson, 2023).

This example illustrates why dietary exposure should not be conceptualized simply as the concentration of a toxin in a single food commodity. The biologically relevant exposure depends on the interaction between contamination levels, food consumption patterns, absorption, metabolism, distribution, excretion and, where applicable, transfer between trophic compartments. In animal-derived foods, the parent compound may also be transformed into metabolites with different toxicological properties. Zearalenone (ZEN), for example, undergoes extensive metabolism in animals, generating metabolites such as α- and β-zearalenol whose biological activity differs from that of the parent compound and contributes to the toxicological profile of exposure (Dänicke & Winkler, 2015; Zinedine et al., 2007).

The movement of mycotoxins through food chains differs fundamentally from the classical transfer of energy between trophic levels. Energy progressively decreases along trophic levels, whereas chemical contaminants may undergo dilution, persistence, concentration, biotransformation or elimination, depending on their physicochemical properties and the biology of the organisms involved. The two processes should therefore not be treated as equivalent. The traditional ecological concept of an energy pyramid should not be interpreted as a quantitative model of mycotoxin transfer; instead, dietary mycotoxin exposure is better represented by a network of interconnected contamination pathways in which the concentration and toxicological activity of a compound may change at each stage.

From food chains to food-exposure networks

Natural ecosystems rarely consist of simple linear food chains. Organisms generally consume multiple food sources, while individual food commodities may originate from complex agricultural and ecological systems. Human diets reflect the same complexity. Most consumers are exposed not to a single mycotoxin or a single contaminated food, but to combinations of food products containing different mycotoxins at different concentrations. Consequently, dietary exposure is better represented by a food-exposure network than by a single linear food chain.

This distinction is particularly important because several mycotoxins frequently co-occur in the same food or feed matrix. Surveys have identified combinations such as aflatoxins with fumonisins, deoxynivalenol (DON) with ZEN, and aflatoxins with ochratoxin A (OTA). Co-occurrence results from the ability of individual fungal species to produce several metabolites, simultaneous contamination by different fungi, and the use of multiple agricultural commodities in animal and human diets (Grenier & Oswald, 2011; Smith et al., 2016).

Multiple exposure changes the toxicological picture. Experimental studies have reported additive, synergistic and antagonistic interactions, depending on the combination of toxins, exposure concentrations, duration, biological model and endpoint evaluated (Smith et al., 2016). Thus, assessment based exclusively on individual mycotoxins may underestimate or otherwise inadequately characterize the complexity of real-world dietary exposure.

The problem becomes even more complex when dietary mycotoxins are considered together with other food contaminants, nutrients, bioactive compounds or pharmaceutical agents. Mycotoxins may affect xenobiotic-metabolizing enzymes, including cytochrome P450 systems, and theoretically may modify the metabolism of concurrently administered drugs. Evidence for clinically important mycotoxin–drug interactions in humans remains limited, and current experimental evidence does not justify assuming that such interactions occur universally. Nevertheless, alterations in CYP450 activity provide a mechanistic basis for further investigation of potential interactions between chronic dietary mycotoxin exposure and pharmacotherapy (Rychlik et al., 2022).

Dietary exposure as a dynamic process

Dietary exposure to mycotoxins should be regarded as a dynamic process rather than as a single event. Contamination may develop during crop production, increase during inappropriate storage, persist during processing, and subsequently contribute to repeated low-dose exposure through habitual consumption. Temperature, water activity, humidity, substrate composition and other environmental conditions influence fungal growth and toxin production. Consequently, changes in agricultural and climatic conditions may alter both the geographical distribution and contamination patterns of food commodities (Eskola et al., 2020; EFSA, 2026).

The stability of many mycotoxins is particularly relevant to dietary exposure. Conventional processing does not necessarily eliminate contamination completely, and some compounds may survive milling, drying, fermentation or other technological treatments. Moreover, processing can redistribute mycotoxins between food fractions or alter the chemical form of the toxin. For this reason, the concentration measured in a raw agricultural commodity cannot always be directly equated with the concentration ultimately ingested by the consumer (Marin et al., 2013; Ferrer et al., 2019).

Dietary exposure assessment consequently combines analytical measurements of mycotoxin contamination with food-consumption data. Estimated daily intake (EDI), probable daily intake (PDI), chronic dietary exposure and acute exposure estimates can then be compared with appropriate health-based guidance values or other risk-characterization approaches. Total-diet studies are particularly useful because they incorporate the contribution of multiple foods consumed as part of habitual diets rather than evaluating isolated commodities (Ferrer et al., 2019).

Human biomonitoring provides another important perspective by measuring mycotoxins or their metabolites in biological matrices such as urine, blood, breast milk or other specimens. Biomonitoring can provide information on internal exposure, thereby complementing estimates derived from food contamination and consumption data. This distinction matters because the ingested dose and the biologically effective dose are not necessarily equivalent: absorption, metabolism, tissue distribution and elimination determine the fraction of the ingested toxin that reaches target tissues (Turner et al., 2012; Ferrer et al., 2019).

From trophic transfer to toxicokinetics

The biological consequences of dietary mycotoxin exposure are determined not only by the amount ingested but also by the toxicokinetic and toxicodynamic characteristics of each compound. Following ingestion, mycotoxins may undergo absorption in the gastrointestinal tract, distribution through the circulation, metabolic transformation and elimination. Phase I and phase II metabolic reactions may either reduce toxicity or generate metabolites with increased biological activity.

Aflatoxin B_1 provides a classical example of bioactivation. Hepatic cytochrome P450 enzymes metabolize AFB_1 to reactive intermediates capable of interacting with cellular macromolecules, including DNA. Such metabolic activation contributes substantially to the carcinogenic potential of AFB_1 (Wu et al., 2014; Marin et al., 2013).

OTA illustrates a different toxicological pattern, with particular concern regarding renal effects and cellular signaling. Its toxicokinetic behavior, persistence and interaction with cellular processes contribute to its biological effects, while its simultaneous occurrence with other mycotoxins raises the possibility of combined exposure (Ringot et al., 2006).

Trichothecenes such as DON exert important effects on protein synthesis and gastrointestinal and immune functions, whereas fumonisins interfere with sphingolipid metabolism through inhibition of ceramide synthase. ZEN and its metabolites have estrogenic activity because of their structural similarity to endogenous estrogens. Despite their common dietary route of exposure, individual mycotoxins can therefore act through substantially different molecular targets and produce distinct toxicological profiles (Wu et al., 2014; Adebo et al., 2022).

Toxicological and pharmacological consequences of dietary exposure

The toxicological consequences of dietary mycotoxin exposure extend across multiple biological systems. Depending on the compound, dose and duration of exposure, reported effects include hepatotoxicity, nephrotoxicity, gastrointestinal injury, immunotoxicity, genotoxicity, reproductive and developmental toxicity, endocrine disruption and carcinogenicity. Several mycotoxins also affect oxidative balance, mitochondrial function, inflammatory signaling, apoptosis and cellular proliferation (Adebo et al., 2022).

At the cellular level, oxidative stress represents a recurring mechanism of mycotoxin toxicity. Exposure to several major mycotoxins can increase reactive oxygen species, disrupt antioxidant defenses, damage lipids, proteins and nucleic acids, and activate downstream pathways associated with apoptosis and inflammation. These processes may help explain why apparently different mycotoxins can produce overlapping pathological outcomes despite having different primary molecular targets (Adebo et al., 2022).

Dietary exposure may also influence gastrointestinal integrity and nutrient utilization. Experimental and epidemiological evidence has associated exposure to aflatoxins, fumonisins and DON with intestinal disturbances and impaired growth, particularly in vulnerable populations. Proposed mechanisms include inhibition of protein synthesis, altered inflammatory signaling and disruption of intestinal cellular function (Smith et al., 2015).

The term pharmacological consequences in the context of mycotoxin exposure should therefore be understood primarily in terms of biologically active molecular effects rather than therapeutic action. Mycotoxins are pharmacologically active xenobiotics capable of interacting with enzymes, receptors, signaling pathways, nucleic acids and cellular membranes. Some mycotoxin-derived compounds have historically demonstrated useful biological activities, including antimicrobial or other pharmacological properties; however, the same molecular activity that makes a compound biologically active may contribute to adverse effects when exposure occurs unintentionally through food (Bennett & Klich, 2003).

An emerging issue is the potential interaction between mycotoxins and therapeutic drugs. Experimental evidence indicates that some mycotoxins can modify CYP450 activity, raising the possibility that repeated dietary exposure may influence the metabolism of xenobiotics or pharmaceutical substances. However, available evidence remains insufficient to establish the clinical magnitude of most proposed mycotoxin–drug interactions, and this area requires further pharmacokinetic and clinical investigation (Rychlik et al., 2022).

Environmental change, food-chain stability and mycotoxin exposure

The stability of food systems depends on the interaction between agricultural production, environmental conditions, fungal ecology and food-processing practices. Disturbances in these systems can modify the probability and intensity of mycotoxin contamination. Temperature and humidity are particularly important because they influence fungal growth and mycotoxin biosynthesis. Climate change is therefore expected to alter the occurrence and geographical distribution of some mycotoxins, potentially exposing populations to contamination patterns that differ from those historically observed (EFSA, 2026).

From this perspective, the ecological concepts of stability, disturbance and succession can be translated into a food-safety framework. Changes in temperature, precipitation, drought, flooding, pest pressure, crop stress and storage conditions can modify fungal communities and their metabolic activity. These changes may consequently alter the contamination profile of crops and animal feed. The resulting exposure is not necessarily determined by one environmental factor but by the interaction of several ecological and technological variables.

Agricultural and food-processing systems can therefore be viewed as dynamic networks in which changes at one stage may influence subsequent stages. Contamination of crops can affect feed; contaminated feed can influence animal exposure; animal metabolism can generate residues in edible tissues or milk; and contaminated foods can contribute to repeated human exposure. Such interconnected pathways support the application of a food-chain and One Health perspective to mycotoxin risk assessment.

Population vulnerability and the consequences of chronic exposure

The consequences of dietary mycotoxin exposure are not uniform across populations. Internal exposure depends on dietary habits, age, body weight, nutritional status, metabolic capacity, health status and the duration and magnitude of exposure. Infants, children, pregnant women and populations consuming large quantities of particular staple foods may therefore have exposure profiles that differ from those of the general adult population (Ferrer et al., 2019; Wang et al., 2025).

Chronic exposure is of particular concern because mycotoxins may be ingested repeatedly at concentrations below those associated with acute intoxication. The absence of overt acute symptoms does not necessarily imply the absence of biological effects. Long-term exposure may involve cumulative molecular damage, persistent oxidative stress, immune modulation, endocrine effects or carcinogenic processes depending on the toxin and exposure scenario (Wu et al., 2014; EFSA, 2026).

This distinction is particularly important when interpreting dietary exposure studies. A food sample that complies with a regulatory limit for an individual mycotoxin does not necessarily indicate zero risk, because consumers may simultaneously ingest the same toxin from several foods or encounter several mycotoxins during the same period. Consequently, modern risk assessment increasingly considers exposure distributions, vulnerable population groups, biomonitoring data and, where evidence permits, combined exposure to multiple contaminants (Ferrer et al., 2019; Smith et al., 2016).

Conceptual framework for systematic evaluation

Taken together, the evidence indicates that dietary mycotoxin exposure can be conceptualized as a continuum:

environmental conditions → fungal growth → crop contamination → food/feed processing → dietary intake → gastrointestinal absorption → biotransformation → systemic distribution → molecular interaction → toxicological/pharmacological effects → biomarkers and clinical outcomes.

This framework is more appropriate for a systematic review of dietary mycotoxins than a conventional description based solely on trophic levels. It integrates ecological determinants with food-chain transmission, toxicokinetics and toxicodynamics and allows the consequences of exposure to be evaluated across different biological scales.

Importantly, the available evidence supports a distinction between external exposure, representing the amount of mycotoxin present in food and consumed by an individual, and internal exposure, representing the absorbed parent compound and its metabolites. The latter is influenced by absorption, metabolism and elimination and may be assessed through biomarkers. Combining dietary exposure estimates with biomonitoring therefore provides a more complete characterization of actual human exposure than either approach alone (Ferrer et al., 2019; Wang et al., 2025).

The evidence base also has an important limitation. Most toxicological studies have historically examined individual mycotoxins under controlled experimental conditions, whereas real dietary exposure frequently involves mixtures at relatively low concentrations over prolonged periods. Natural co-occurrence is well documented, but the biological consequences of chronic multi-mycotoxin exposure remain incompletely characterized. This evidence gap is particularly relevant for emerging toxins such as Alternaria metabolites, enniatins and beauvericin, for which occurrence data, exposure estimates and chronic toxicological evidence remain less developed than for the major regulated mycotoxins (EFSA, 2026; van der Fels-Klerx et al., 2025).

A systematic assessment of dietary mycotoxin exposure should integrate four interconnected dimensions: (1) occurrence in foods and feeds, (2) dietary and internal exposure, (3) toxicokinetic and toxicodynamic mechanisms, and (4) pharmacological and toxicological consequences. Such an integrated approach can help bridge the gap between contamination measurements and biologically meaningful health outcomes.

ENVIRONMENTAL RISKS AS A COMPONENT OF CORPORATE ECONOMIC SECURITY

Globalization, climate change, ecosystem degradation, resource constraints, and the progressive tightening of environmental regulation are substantially altering the risk environment in which firms operate. Environmental pressures that were previously considered primarily within the domain of corporate social responsibility increasingly have direct implications for financial performance, operational continuity, access to capital, supply-chain resilience, and long-term business viability. Consequently, environmental risks should be considered an integral component of corporate risk management and strategic decision-making rather than as an isolated environmental or reputational issue.

Climate-related financial reporting frameworks increasingly recognize this connection. In particular, IFRS S2 Climate-related Disclosures distinguishes between physical and transition risks and requires consideration of their potential effects on an entity's cash flows, access to finance, cost of capital, business model, and strategy (IFRS Foundation, 2023). Physical risks may result from acute events, such as floods and wildfires, or from chronic changes, including rising temperatures and changing precipitation patterns. Transition risks arise from the movement toward a lower-carbon economy and may include policy, legal, technological, market, and reputational changes (IFRS Foundation, 2023, 2025).

This development reflects a broader transformation in the concept of corporate economic security. Traditionally, economic security was predominantly associated with the protection of financial resources, physical assets, personnel, information, and market positions. Contemporary approaches, however, increasingly recognize that the stability of these components depends on the organization's capacity to anticipate and respond to external environmental and systemic risks.

Evolution of the Concept of Corporate Economic Security

The development of corporate economic security can be broadly conceptualized through four stages.

First, the traditional protective approach primarily emphasized safeguarding tangible assets and financial resources. Typical concerns included physical security, theft prevention, fraud control, payment discipline, and protection against internal threats. Risk management under this paradigm was largely reactive and focused on preserving existing organizational resources.

Second, the expanded approach, which became increasingly important during the 1990s and 2000s, reflected globalization, intensified competition, and rapid digitalization. Economic security came to incorporate additional dimensions, including information security, human-resource security, market stability, and protection of intellectual and commercial assets. Economic security was consequently understood less as physical protection and more as the capacity of an organization to maintain stable operations and achieve its strategic objectives.

Third, the strategic and integrated approach, which has become increasingly prominent since the 2010s, conceptualizes economic security as an integrated risk-management system concerned with long-term organizational resilience. Under this perspective, organizations are expected to identify emerging risks before they materialize, integrate risk assessment into strategic planning, and protect intangible resources such as reputation, intellectual property, organizational knowledge, and brand value.

Fourth, the environmental-risk perspective extends this framework by treating environmental and climate-related risks as cross-cutting factors that can affect virtually all dimensions of corporate economic security. This perspective is consistent with contemporary sustainability reporting frameworks, which require organizations to consider how sustainability-related risks may affect business models, value chains, financial performance, and access to finance (IFRS Foundation, 2023).

Thus, environmental sustainability should not be interpreted exclusively as an additional corporate objective. Rather, environmental conditions can influence the resilience of the organization's underlying economic model. This is particularly relevant for sectors that depend heavily on natural resources, energy, water availability, agricultural production, or environmentally sensitive supply chains.

Integrating Environmental Risk into Corporate Economic Security

The integration of environmental risk into corporate economic security can be structured around several interconnected principles.

Proactive risk identification and strategic anticipation.

Effective environmental risk management requires organizations to identify both current and emerging risks and incorporate them into strategic planning. Scenario analysis can be used to examine how alternative climate and transition pathways could affect assets, operations, supply chains, revenues, and capital requirements. IFRS S2 explicitly requires entities to provide information concerning their processes for identifying, assessing, prioritizing, and monitoring climate-related risks and opportunities and to assess the resilience of their strategies to climate-related changes and uncertainties (IFRS Foundation, 2023).

Translation of environmental risks into financial consequences.

A central element of integrated environmental risk management is the translation of environmental exposure into economically meaningful indicators. For example, physical climate risks may affect asset values, insurance costs, production capacity, and supply-chain expenses, while transition risks may influence operating costs, capital expenditure, asset impairment, market demand, and financing conditions. IFRS S2 specifically focuses on climate-related risks that could reasonably be expected to affect an entity's cash flows, access to finance, or cost of capital (IFRS Foundation, 2023).

Value-chain integration.

Environmental risk assessment should extend beyond the organization's direct operations. Modern sustainability frameworks recognize that significant sustainability-related risks and opportunities can occur throughout an entity's value chain. This is particularly important for indirect greenhouse-gas emissions and other environmental impacts associated with suppliers, transportation, purchased inputs, product use, and waste management (IFRS Foundation, 2023).

Resource efficiency and circularity as resilience mechanisms.

Resource efficiency, waste reduction, recycling, reuse, and low-carbon technologies can simultaneously reduce environmental pressures and exposure to resource-price volatility, regulatory changes, and supply disruptions. Within a green-economy framework, therefore, environmental investments can be examined not only as compliance expenditures but also as components of long-term organizational resilience and resource productivity.

Integration of environmental indicators into management systems.

Environmental performance indicators can be incorporated into enterprise risk management, strategic planning, investment decisions, and performance evaluation. Relevant indicators may include greenhouse-gas emissions, energy and water intensity, exposure to climate hazards, waste generation, resource dependence, environmental incidents, and progress toward environmental targets. IFRS S2 similarly requires disclosures concerning governance, strategy, risk-management processes, and metrics and targets related to climate risks and opportunities (IFRS Foundation, 2023).

Environmental Risks and Corporate Economic Security

Environmental risks can affect different components of corporate economic security through multiple transmission channels. For analytical purposes, these risks can be divided into physical risks and transition risks, with transition risks further differentiated according to their regulatory, technological, market, and reputational dimensions.

Physical risks

Physical risks arise from the direct effects of environmental and climatic changes on organizational activities. They can be divided into:

Acute physical risks, including floods, storms, wildfires, extreme precipitation, and other severe events;

Chronic physical risks, including long-term temperature increases, changing precipitation patterns, water scarcity, sea-level rise, and progressive ecosystem degradation.

Such risks can damage physical assets, interrupt production, reduce labor productivity, disrupt transportation, increase insurance costs, and affect the availability and price of critical inputs. IFRS S2 explicitly distinguishes acute physical risks from chronic physical risks and considers their potential effects over short-, medium-, and long-term horizons (IFRS Foundation, 2023).

Transition risks

Transition risks arise from the structural transformation toward a lower-carbon and more environmentally sustainable economy. They include policy and legal, technological, market, and reputational risks (IFRS Foundation, 2025).

Policy and regulatory risks may emerge from stricter emissions standards, environmental taxation, carbon-pricing mechanisms, disclosure requirements, and other regulatory measures.

Technological risks may arise when existing production technologies or assets become less competitive because cleaner alternatives become commercially viable or regulatory requirements change.

Market risks may result from changes in consumer preferences, commodity prices, energy markets, or demand for environmentally intensive products.

Reputational risks may arise from environmental incidents, inadequate environmental performance, or discrepancies between corporate sustainability claims and actual environmental practices.

These categories should not be viewed as independent. A regulatory change may accelerate technological substitution, which may alter consumer demand and subsequently affect the value of existing assets. Consequently, environmental risks may propagate through several components of the corporate risk architecture simultaneously.

Transmission Channels from Environmental Risk to Economic Security

The relationship between environmental risk and corporate economic security can therefore be understood as a cascade of interconnected effects. A physical environmental event may initially cause direct damage to assets or interrupt production. This may subsequently generate higher operating costs, delays in fulfilling contractual obligations, supply-chain disruptions, revenue losses, and additional financing requirements. In parallel, environmental incidents can affect stakeholder confidence and increase reputational exposure. Transition risks can operate through a different but equally important mechanism. Regulatory changes, technological substitution, changes in consumer preferences, and changes in investor expectations can alter the economic value of existing assets and business models. IFRS S2 consequently requires consideration of climate-related risks that can affect business models, strategy, cash flows, access to finance, and cost of capital (IFRS Foundation, 2023).

The resulting framework can be summarized as:

Environmental change → physical/transition risk → operational and value-chain effects → financial consequences → implications for corporate economic security.

Table 2. Environmental Risk Categories and Their Implications for Corporate Economic Security

Environmental risk category	Main manifestations	Principal transmission channels	Potential implications for corporate economic security
Acute physical risks	Floods, storms, wildfires, extreme precipitation	Asset damage, production interruption, logistics disruption	Revenue losses, repair costs, increased insurance costs, operational instability
Chronic physical risks	Rising temperatures, water scarcity, changing precipitation, sea-level rise	Resource constraints, declining productivity, relocation requirements	Higher operating costs, reduced production capacity, asset impairment
Policy and regulatory risks	Environmental standards, carbon pricing, emissions regulation, disclosure requirements	Compliance costs, investment requirements, changes in operating conditions	Increased expenditure, regulatory exposure, changes in capital allocation
Technological risks	Rapid development and adoption of low-carbon technologies	Technological substitution, asset obsolescence	Stranded assets, additional capital expenditure, loss of technological competitiveness
Market risks	Changes in consumer demand, commodity prices, energy markets	Changes in sales, input costs, and market structure	Revenue volatility, margin pressure, changes in business-model viability
Reputational risks	Environmental incidents, stakeholder pressure, greenwashing allegations	Loss of stakeholder trust, investor response, reduced market acceptance	Brand damage, financing constraints, loss of customers or investors

Source: Adapted by the authors from the climate-related risk classifications and disclosure principles of the IFRS Foundation (2023, 2025).

This causal chain demonstrates why environmental risk management should be connected to the broader corporate risk-management architecture rather than being treated exclusively as an environmental compliance function.

Implications for Green Economy and Sustainable Corporate Development

From a green-economy perspective, the integration of environmental risks into corporate economic security creates a connection between environmental sustainability, economic resilience, and long-term value creation. The objective is not simply to minimize environmental damage but to identify how environmental conditions and the transition toward sustainability influence the durability of business models.

This approach is particularly relevant to investment and capital-allocation decisions. Organizations increasingly need to assess whether existing assets and technologies remain economically viable under changing environmental regulations, resource constraints, technological developments, and market conditions. IFRS S2 requires information that enables users of financial reports to assess the effects of climate-related risks and opportunities on an entity's prospects, including its financial position, financial performance, cash flows, access to finance, and cost of capital (IFRS Foundation, 2023).

Accordingly, environmental risk management can be incorporated into corporate economic security through four interconnected levels:

1. Risk identification — identification of physical, regulatory, technological, market, and reputational environmental risks;
2. Risk assessment — evaluation of probability, exposure, vulnerability, time horizon, and potential financial consequences;
3. Strategic integration — incorporation of environmental risks into investment, procurement, production, financing, and business-continuity decisions;
4. Monitoring and adaptation — continuous assessment of environmental indicators, regulatory developments, technological change, and progress toward sustainability objectives.

This framework is consistent with the broader evolution of sustainability-related financial reporting toward integrated consideration of governance, strategy, risk management, and metrics and targets (IFRS Foundation, 2023).

Analytical Implications

The analysis indicates that environmental risks can affect multiple dimensions of corporate economic security simultaneously. Their effects may extend from direct physical damage to financial performance, supply-chain stability, technological competitiveness, access to finance, and stakeholder relations. Importantly, these effects may be interconnected rather than isolated.

At the same time, it would be inappropriate to assume that transition risks universally have greater economic significance than physical risks. Their relative importance depends on the company's sector, geographical exposure, asset structure, supply-chain configuration, regulatory environment, and planning horizon. Contemporary reporting standards therefore require organizations to identify and assess both physical and transition risks rather than presuming the dominance of one category (IFRS Foundation, 2023).

For companies operating in resource-intensive sectors, environmental risk management may therefore represent an important component of long-term economic resilience. The integration of environmental indicators into enterprise risk management can improve the organization's capacity to anticipate disruptions, evaluate investment alternatives, allocate capital, and adapt its business model to changing environmental and regulatory conditions.

CONCLUSIONS

The findings of this systematic review indicate that dietary exposure to mycotoxins is an important food-safety and public-health concern because these compounds can produce hepatotoxic, nephrotoxic, immunomodulatory, genotoxic, reproductive, endocrine and carcinogenic effects, depending on the toxin, dose, duration of exposure and individual susceptibility (Rocha et al., 2014; WHO, 2023). Chronic exposure deserves particular attention because adverse effects may develop without obvious clinical symptoms, while aflatoxins and several other mycotoxins have well-documented toxicological consequences (IARC, 2012; WHO, 2023).

For regulatory authorities, control should extend beyond finished products and cover the entire food chain, from primary production and harvesting to drying, storage, transport and processing (Codex Alimentarius Commission, 2017; WHO, 2023). A farm-to-fork strategy based on good agricultural practices, timely harvesting, rapid drying, appropriate storage, pest management and resistant crop varieties can reduce fungal growth and mycotoxin formation before contaminated commodities enter the food supply.

Particular attention should be given to multimycotoxin exposure, since several toxins may occur simultaneously in the same commodity and their combined effects can complicate risk assessment (Arce-López et al., 2024). Multi-analyte approaches, including LC–MS/MS, should therefore be increasingly incorporated into surveillance systems, while rapid and affordable screening methods remain important where laboratory capacity is limited. Human biomonitoring can further complement food-occurrence data by providing information on actual internal exposure and differences in dietary patterns and metabolism.

Climate change adds another layer of uncertainty. Changes in temperature, precipitation, drought and humidity can influence fungal ecology and the geographical occurrence of mycotoxins, particularly aflatoxins and Fusarium toxins (EFSA, 2026; Yan & Sun, 2025). Climate-informed surveillance combining meteorological, crop and analytical data could therefore support earlier identification of high-risk periods and areas and enable more targeted preventive measures.

At the same time, sustainable management should prioritize prevention rather than relying mainly on the rejection and disposal of contaminated commodities. Improved storage, resistant varieties, biological control and scientifically validated mitigation technologies may help reduce both contamination and food losses, although their effectiveness varies among mycotoxins. Prevention remains the most sustainable strategy.

Vulnerable population groups, including children and pregnant women, require particular consideration in exposure assessment and risk communication. Clear guidance for farmers, food processors and consumers on storage, handling and the risks associated with visibly mouldy foods can support practical risk reduction.

A One Health perspective is equally important because mycotoxin risks link human health with animal health, agricultural production and environmental conditions. Coordination among food-safety, veterinary, agricultural, environmental and public-health authorities can strengthen surveillance and risk management (WHO, 2023; EFSA, 2026).

Overall, the evidence supports a shift from predominantly end-product testing towards preventive, integrated and risk-based food-chain management. Combining good agricultural and storage practices, multimycotoxin surveillance, exposure assessment, climate-informed early-warning systems, validated mitigation measures and One Health coordination can reduce dietary exposure while improving the resilience and sustainability of food systems.

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Financial-risk aware machine learning for industrial anomaly detection

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ABSTRACT

Digital transformation in asset-intensive industries is constrained by the separation between Information Technology (IT), which supports enterprise decision-making, and Operational Technology (OT), which monitors and controls physical assets. This study proposes a Financial-Risk Aware Digital Twin framework that combines machine-learning-based anomaly detection with event-specific economic consequence analysis. Using the benchmark 3W oil and gas dataset, an XGBoost classifier was developed to identify operational states including severe slugging, spurious Downhole Safety Valve closure, flow instability, productivity loss, scaling, and hydrate formation. The model achieved 93% overall accuracy, with weighted-average precision and F1-score of 0.94 and 0.93, respectively. Predicted class probabilities were then converted into class-specific expected financial exposure using illustrative consequence scenarios. At a predicted probability of 20%, the corresponding exposure was $200,000 for hydrate formation, $100,000 for DHSV closure, and $10,000–$20,000 for one day of severe slugging under the selected scenario assumptions. Financial weighting also changed event prioritization in an illustrative re-ranking example. For hydrate formation, a base-case failure consequence of $1,000,000 and preventive-action cost of $5,000 produced a 0.5% break-even intervention probability; sensitivity analysis across alternative assumptions yielded thresholds from 0.125% to 2.0%. The results show how probabilistic condition monitoring can be extended into an economically informed decision-support framework that prioritizes operational responses according to both likelihood and consequence.

INTRODUCTION

Industrial digital transformation increasingly depends on the integration of cyber-physical systems, real-time data analytics, and connected operational assets. Research on Industry 4.0 demonstrates that successful digital transformation requires not only technological adoption but also corresponding organizational and managerial capabilities (Agostini & Filippini, 2019). Within this transformation, Digital Twin technologies provide a mechanism for linking physical assets with virtual representations through continuous data exchange, sensing, and analytics (Fuller et al., 2020; Lu et al., 2020).

A persistent challenge is the distinction between Information Technology (IT) and Operational Technology (OT). OT systems directly monitor or control physical processes and therefore operate under performance, reliability, availability, and safety requirements that differ from those of conventional enterprise IT systems (Stouffer et al., 2023). As a result, high-frequency operational information may remain disconnected from enterprise-level assessments of financial and strategic risk. A pressure or temperature anomaly, for example, can be technically meaningful to an operations engineer while its potential economic consequence is not immediately represented in enterprise decision processes.

Probabilistic machine-learning models offer an opportunity to reduce this gap, but prediction probability alone does not represent economic consequence. Cost-sensitive decision theory distinguishes between statistical classification and the subsequent decision made using estimated class probabilities and the costs associated with alternative outcomes (Elkan, 2001). Similarly, modern AI risk-management frameworks emphasize that risks should be evaluated using both likelihood and impact rather than model performance alone (Tabassi, 2023). This provides the conceptual basis for coupling operational anomaly probabilities with event-specific financial consequences.

Accordingly, this study addresses the following research question: Can probabilistic outputs from an industrial anomaly-detection model be translated into economically meaningful risk priorities without modifying the underlying diagnostic classifier? To address this question, a Financial-Risk Aware Digital Twin framework is developed using the 3W oil-well anomaly dataset and an XGBoost multiclass classifier. Predicted class probabilities are translated into class-specific expected financial exposure and subsequently used to examine economic risk re-ranking and intervention thresholds.

A preliminary version of this work was published in the proceedings of the First International Conference on Artificial Intelligence for Digital Transformations (AIDT 2026) (Allahverdiyev, 2026). The present journal manuscript substantially extends that work through multi-event financial-risk quantification, economic risk re-ranking, intervention-threshold analysis, sensitivity analysis of financial assumptions, and expanded discussion of the resulting economic decision framework.

LITERATURE REVIEW

Bridging the IT/OT Semantic Gap

OT environments encompass systems that sense, monitor, or directly control physical processes, including industrial control systems and SCADA architectures. Because changes in OT can directly affect equipment and physical operations, reliability, availability, performance, and safety are central design requirements (Stouffer et al., 2023). These operational priorities can differ from enterprise IT requirements and complicate the integration of operational data with higher-level analytical and business systems.

Digital Twin architectures provide one pathway for integrating these environments. Digital Twins combine physical-system information with virtual representations and analytics, supported by technologies such as the Internet of Things, industrial communication, and data-processing systems (Fuller et al., 2020; Lu et al., 2020). In an asset-management context, this integration enables operational measurements to be interpreted not only as engineering variables but also as inputs to maintenance and decision-support processes. The remaining challenge is therefore not simply transferring OT data into an IT environment but translating those data into information that is meaningful for operational and economic decisions.

Predictive Risk and Cost-Sensitive Decision Making

Conventional multiclass classifiers typically prioritize statistical prediction performance, whereas the economic consequences of different errors may vary substantially. In industrial operations, a false negative involving a high-consequence failure can be more important than several low-consequence classification errors. Cost-sensitive decision theory provides a formal mechanism for addressing this asymmetry by combining class-probability estimates with a cost or loss matrix (Elkan, 2001).

Importantly, cost sensitivity does not necessarily require altering the training objective of the underlying classifier. Elkan (2001) shows that a standard probabilistic classifier can first be learned from the available data and its probability estimates can then be used to select decisions that minimize expected cost. This distinction is directly relevant to the present study: XGBoost performs the anomaly classification, while a separate financial decision layer translates its probabilistic outputs into expected economic exposure. The proposed framework should therefore be understood as cost-sensitive decision support rather than cost-sensitive XGBoost training.

This approach is also consistent with broader AI risk-management principles. The NIST AI Risk Management Framework emphasizes prioritizing risk according to both impact and likelihood and selecting responses according to the resulting risk assessment (Tabassi, 2023). In the present framework, predicted anomaly probability represents the likelihood component, while the assigned economic consequence represents the impact component.

Autonomous Execution and Human-Centric Governance

Economic decision support in safety-relevant industrial systems should not be interpreted as a replacement for engineering judgment. AI risk-management guidance emphasizes governance, documentation, validation, and appropriate human oversight throughout the deployment lifecycle (Tabassi, 2023). These requirements are particularly important when automated recommendations may affect production continuity, maintenance expenditure, or physical safety.

The European Union's Artificial Intelligence Act also applies risk-based requirements to specified AI applications. Importantly, the Act does not classify all industrial AI as high risk. High-risk status applies under defined conditions, including certain AI systems used as safety components of regulated products and specified applications associated with critical infrastructure (European Parliament & Council of the European Union, 2024). Accordingly, the framework proposed in this study is positioned as decision support: it translates predicted operational states into economic risk indicators, while final safety-critical intervention decisions remain subject to operator procedures, engineering validation, and applicable regulatory requirements.

METHODOLOGY

The 3W Dataset and Multi-Sensor Inputs

The study uses the 3W Dataset, a publicly available benchmark developed for the detection and diagnosis of rare undesirable events in naturally flowing offshore oil wells. The original dataset contains real, simulated, and hand-drawn multivariate time-series instances and was designed to support research on eight categories of undesirable operational events (Vargas et al., 2019). The dataset provides a suitable benchmark for the present study because it combines realistic industrial measurements with rare-event labels that are difficult to obtain in conventional operating datasets.

Three continuously available sensor variables were selected for the present analysis: *P-PDG*, representing pressure measured by the Permanent Downhole Gauge; *P-TPT*, representing pressure measured at the Temperature and Pressure Transducer; and *T-TPT*, representing temperature at the same transducer. Statistical characteristics derived from these signals were used as inputs to the anomaly classifier. Figure 1 illustrates representative sensor trajectories for the eight operational classes considered in the study, highlighting the distinct pressure and temperature patterns associated with normal operation and the modeled undesirable events.

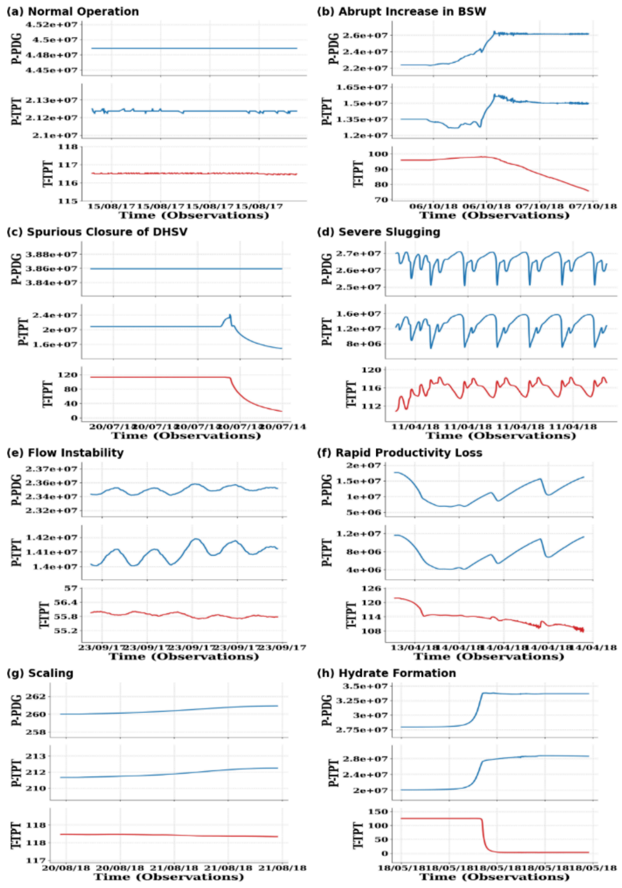

Figure 1. Eight-class failure mode classification in the 3W Dataset. Subplots a-h demonstrate the divergent sensor patterns associated with normal conditions or specific industrial risks

The three sensor signals were transformed into statistical features using a fixed window comprising the first 60 observations of each valid data file. Files containing fewer than 60 observations or lacking any of the three required sensor channels (P-PDG, P-TPT, and T-TPT) were excluded from the analysis. Missing sensor values were handled by forward filling followed by backward filling. For each 60-observation window, four statistical descriptors—mean, standard deviation, skewness, and kurtosis—were calculated independently for each of the three sensors, resulting in a 12-feature input vector for every data instance. Undefined skewness or kurtosis values arising from constant or near-constant signals were replaced with zero. In total, 1,800 valid instances were generated. The data were divided into training and test subsets using a GroupShuffleSplit with an 80:20 split and a random seed of 42, resulting in 1,440 training instances and 360 test instances. The source file path was used as the grouping variable so that an individual file could not appear in both subsets. Because one feature vector was extracted from each source file, this procedure provides file-level separation; well-level grouping was not implemented in the present analysis. Class labels were subsequently encoded into contiguous numerical categories. Finally, the 12 input features were standardized using a StandardScaler fitted exclusively on the training subset and then applied unchanged to the test subset.

The Financial Translation Engine

An XGBoost classifier was used as the multiclass anomaly-detection model. XGBoost implements gradient-boosted decision trees and is designed for efficient and scalable supervised learning (Chen & Guestrin, 2016). The classifier was configured using the multi:softprob objective, with n_estimators = 200, learning_rate = 0.1, and max_depth = 6. No explicit financial class weighting was applied during model training.

The probabilistic output of XGBoost was subsequently passed to a separate economic decision layer. For operational state k, let p_k denote the predicted class probability and C_k denote an assigned financial consequence. The class-specific expected financial exposure was defined as:

$$EFE_k = p_k C_k \quad (1)$$

This post-classification structure follows the general principle of cost-sensitive decision making in which probabilistic model outputs are combined with a cost matrix to inform downstream decisions (Elkan, 2001). Consequently, the term *financial-risk aware* in this study refers to the decision layer applied to the classifier output, rather than to a financially weighted XGBoost training objective.

Financial Taxonomy of Operational Anomalies

The 3W classification problem distinguishes normal operation from several undesirable operational states. In the present framework, the technical classes remain those represented in the 3W benchmark, while a separate economic layer is used to characterize the potential consequence of selected high-impact events (Vargas et al., 2019).

Three classes were selected for explicit monetary scenario analysis: severe slugging, spurious DHSV closure, and hydrate formation. Severe slugging is characterized by large fluctuations in pressure and flow rate and can be mitigated through manual or automatic choking strategies (Zhao et al., 2024). Failure of a surface-controlled subsurface safety valve can result in a shut-in well and may require retrofit or workover-based remediation, with associated deferred production and intervention consequences (Champion et al., 2011). Hydrate formation is a major subsea flow-assurance challenge, and chemical inhibitor strategies are used to reduce the risk of hydrate plugging during unfavorable operating or shutdown conditions (Kim et al., 2020).

The monetary values employed in the present analysis are scenario parameters rather than universal industry-average costs. Severe slugging was evaluated using a one-day consequence range of \$50,000–\$100,000, DHSV closure using an event consequence of \$500,000, and severe hydrate remediation using an event consequence of \$1,000,000. For the hydrate intervention-threshold experiment, \$5,000 was used as the base-case preventive-action cost. These values are intentionally subjected to sensitivity analysis and should be replaced by asset-specific estimates in practical deployment. The purpose of the monetary scenarios is therefore to test the decision logic of the proposed framework, not to establish standardized industry cost values.

The remaining operational classes, including BSW increase, flow instability, productivity loss, and scaling, were retained in the multiclass anomaly-detection problem but were not assigned fixed monetary values in the cross-class financial experiment. Their actual economic impact depends strongly on production rate, fluid properties, commodity prices, treatment strategy, asset configuration, and intervention duration.

RESULTS AND DISCUSSION

Statistical Signature Analysis and Feature Validation

As shown in Figure 2, the distributions of P-PDG, P-TPT, and T-TPT vary considerably across the modeled operational classes.

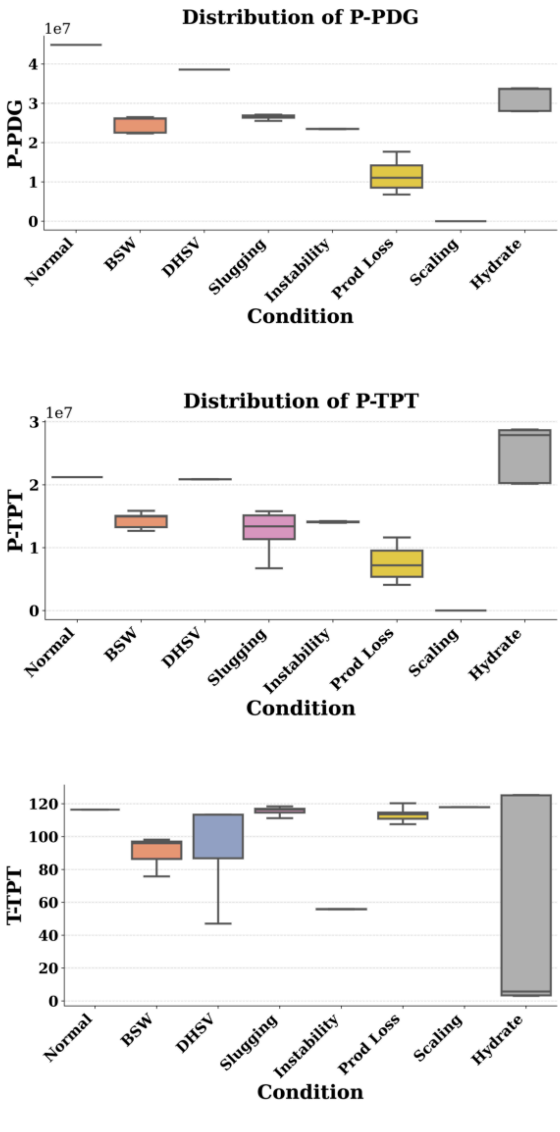

Figure 2. Distribution of P-PDG, P-TPT, and T-TPT measurements across the modeled operational classes

Normal-operation observations exhibit comparatively stable sensor behavior, whereas several undesirable states show wider distributions or pronounced shifts in pressure and temperature. Severe slugging and flow-instability cases display greater pressure variability than the normal condition, while productivity-loss cases exhibit a marked reduction in pressure. Hydrate observations also show substantial variability in the temperature signal. These distributional differences support the use of statistical descriptors such as mean, standard deviation, skewness, and kurtosis as input features for the anomaly-detection model.

Model Performance Evaluation

The predictive performance of the XGBoost classifier was evaluated using the held-out test dataset. Figure 3 presents the multiclass confusion matrix, while Table 1 summarizes the corresponding precision, recall, F1-score, and support values. The model achieved an overall classification accuracy of 93%, with weighted-average precision, recall, and F1-score of 0.94, 0.93, and 0.93, respectively. These results indicate strong overall discrimination among the eight operational states, although performance varied across individual classes.

Normal Operation was identified with high precision and recall, indicating that the model produced relatively few false alarms for healthy operating conditions. This is particularly important within the proposed financial-risk framework because unnecessary fault alerts could lead to avoidable operational intervention or production deferment. Strong performance was also observed for BSW and Productivity Loss, while the smaller DHSV and Scaling classes exhibited greater uncertainty because of their limited representation in the test sample.

Hydrate Formation exhibited a precision of 1.00 and a recall of 0.77. Thus, no false-positive hydrate predictions occurred in the test set, while approximately 23% of the true hydrate observations were assigned to another operational class. Several of these cases were classified as DHSV or slugging events. This overlap indicates that high-consequence classes can share transient pressure and temperature characteristics and highlights the importance of considering both classification uncertainty and consequence severity. Because the present study did not prospectively test automated field interventions, these results should not be interpreted as evidence that a real control system would necessarily execute the correct operational response following a misclassification.

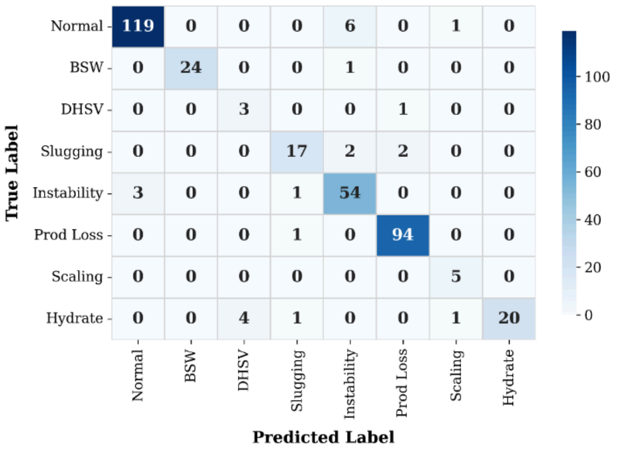

Figure 3. Confusion matrix for the XGBoost-based multiclass anomaly-detection model

Table 1. Classification performance metrics for the eight modeled operational states

Class	Precision	Recall	F-1 score	Support
Normal	0.98	0.94	0.96	126
BSW	1.00	0.96	0.98	25
DHSV	0.43	0.75	0.55	4
Slugging	0.85	0.81	0.83	21
Instability	0.86	0.93	0.89	58
Prod Loss	0.97	0.99	0.98	95
Scaling	0.71	1.00	0.83	5
Hydrate	1.00	0.77	0.87	26
Accuracy			0.93	360
Macro Avg	0.85	0.89	0.86	360
Weighted Avg	0.94	0.93	0.93	360

The class-specific metrics in Table 1 should be interpreted together with their corresponding support values. Rare classes such as DHSV and Scaling contain only a small number of test observations, meaning that their precision and recall estimates are inherently less stable than those of more highly represented classes. The weighted-average metrics therefore provide a more representative measure of overall predictive performance, while additional observations of rare failure states would be required for stronger class-specific validation.

Feature Importance Analysis

To examine the variables contributing most strongly to model decisions, global feature importance was extracted from the XGBoost ensemble. The resulting ranking is presented in Figure 4. The analysis indicates that the classifier uses information from both pressure and temperature signals and that multiple statistical descriptors contribute to class discrimination. Mean signal levels capture systematic shifts among operating states, while standard deviation, skewness, and kurtosis provide additional information on signal variability and distribution shape. The contribution of these complementary descriptors supports the use of statistical feature engineering rather than reliance on instantaneous sensor measurements alone.

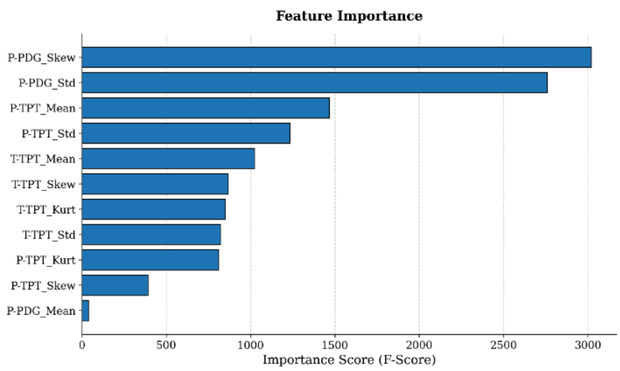

Figure 4. Feature importance ranking for the model

Economic Risk Analysis

To extend the analysis beyond conventional classification metrics, predicted event probabilities were translated into expected financial exposure for three high-consequence operational states: severe slugging, spurious DHSV closure, and hydrate formation. The monetary values used in this analysis correspond to the illustrative scenario assumptions defined in the Financial Taxonomy section rather than universal industry-average costs. Severe slugging was evaluated using a one-day consequence range of \$50,000–\$100,000, DHSV closure using an event consequence of \$500,000, and severe hydrate remediation using an event consequence of \$1,000,000.

For operational state k, expected financial exposure was calculated as $EFE_k = p_k C_k$, where p_k is the predicted event probability and C_k is the assigned economic consequence. To enable cross-class comparison, the probabilities were interpreted over a common one-day decision horizon. The DHSV and hydrate values were treated as event consequences conditional on occurrence within that horizon, whereas the severe-slugging value represented one day of deferred-production loss.

The scenario analysis demonstrates that identical predicted probabilities can correspond to markedly different economic exposures. At a predicted probability of 0.10, the expected financial exposure is approximately $100,000 for hydrate formation, $50,000 for DHSV closure, and $5,000–$10,000 for one day of severe slugging. At a probability of 0.20, the corresponding exposures increase to approximately $200,000, $100,000, and $10,000–$20,000, respectively. At a probability of 0.50, the expected exposures reach approximately $500,000 for hydrate formation, $250,000 for DHSV closure, and $25,000–$50,000 for severe slugging. Figure 5 illustrates this relationship across the full probability range.

These results demonstrate that probability alone does not preserve the economic ordering of operational risk. A relatively low-probability, high-consequence event may create greater expected financial exposure than a more probable but less costly event. Accordingly, operational priority can differ substantially depending on whether decisions are based solely on diagnostic probability or on the combination of probability and financial consequence.

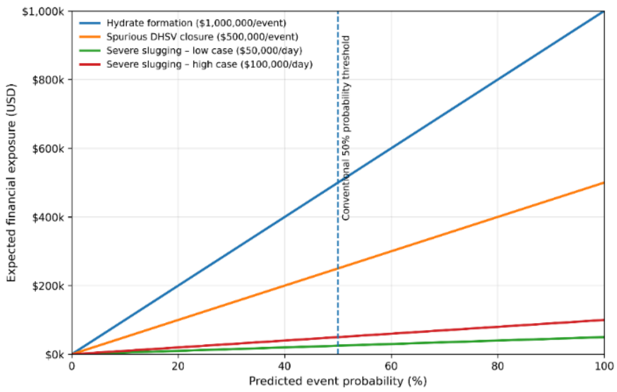

Figure 5. Expected financial exposure as a function of predicted event probability for high-consequence operational events

Risk Re-ranking Analysis

The practical effect of financial weighting can also be illustrated through risk re-ranking. Consider an illustrative output in which the predicted probabilities of severe slugging, DHSV closure, and hydrate formation are 0.45, 0.35, and 0.20, respectively. A probability-only ranking prioritizes severe slugging, followed by DHSV closure and hydrate formation. Using a representative one-day slugging consequence of $75,000, however, the corresponding expected financial exposures are $33,750, $175,000, and $200,000, respectively. The financial-risk ranking therefore becomes hydrate formation, DHSV closure, and severe slugging. This example demonstrates that the most probable failure state is not necessarily the most economically consequential state.

Economic Intervention Threshold

An illustrative intervention threshold was derived by comparing expected failure exposure with the cost of preventive action. Under a risk-neutral expected-cost assumption, intervention becomes economically favorable when the expected financial exposure exceeds the intervention cost. The corresponding break-even probability can therefore be expressed as $p^* = C_I/C_F$, where C_I is the preventive-intervention cost and C_F is the financial consequence of an untreated failure.

For the hydrate scenario, the base-case assumptions of a $1,000,000 failure consequence and a $5,000 preventive-action cost yield a break-even probability of 0.005, or 0.5%. Under these assumptions, preventive action becomes economically justified at a probability substantially below the illustrative 50% probability threshold used for comparison. This value should not be interpreted as a universal hydrate-management criterion because actual intervention effectiveness, production value, chemical-treatment cost, asset configuration, and operating conditions differ across facilities.

Sensitivity Analysis of Financial Assumptions

Because the economic decision rule depends on estimated failure and intervention costs, a sensitivity analysis was performed for the hydrate scenario. The assumed failure consequence was varied from $500,000 to $2,000,000, while the preventive-intervention cost was varied from $2,500 to $10,000. These values represent scenario bounds around the base case rather than standardized industry estimates. Figure 6 presents the resulting break-even intervention probabilities.

Across the investigated combinations, the break-even probability ranged from 0.125% to 2.0%. Under the base-case assumptions of a $5,000 preventive intervention and a $1,000,000 failure consequence, the threshold is 0.5%. When the failure consequence is reduced to $500,000 and the intervention cost is increased to $10,000, the break-even probability increases to 2.0%. Conversely, a $2,000,000 failure consequence combined with a $2,500 intervention cost reduces the threshold to 0.125%.

Figure 6. Sensitivity of the economically justified hydrate intervention threshold to variations in preventive intervention cost and assumed failure/remediation consequence

Although the numerical threshold changes with the selected economic assumptions, the overall decision pattern remains consistent across the evaluated scenarios. High-consequence events can become economically significant at probabilities substantially below the illustrative 50% reference threshold. The proposed framework therefore does not depend on one fixed financial value; instead, the cost parameters can be replaced with operator-specific estimates appropriate to a particular asset or operating environment.

Discussion of Economic Decision Implications

The combined classification and financial analyses demonstrate an important distinction between diagnostic probability and economic decision priority. The machine-learning model estimates the likelihood of alternative operational states, whereas the economic decision layer evaluates the potential consequence associated with those states. An event with a lower predicted probability may therefore warrant greater operational attention than a more probable event if its economic consequence is substantially larger.

The sensitivity results further indicate that the proposed framework is better interpreted as an adaptable decision-support architecture than as a fixed-cost prescription. In practical deployment, operators could replace the illustrative consequence values with asset-specific estimates incorporating production rate, commodity price, intervention duration, treatment cost, contractual exposure, and organizational risk tolerance. The anomaly-detection model itself would not necessarily need to be retrained simply because the economic assumptions change.

Several limitations should nevertheless be recognized. First, the rarest classes contain relatively few test observations, which limits confidence in their class-specific performance estimates. Second, the financial analysis uses illustrative scenario costs rather than realized field-level economic losses. Third, the present study does not evaluate probability calibration. Because expected-cost calculations depend on the reliability of predicted probabilities, future deployment should assess probability calibration before financial exposure estimates are used operationally. Finally, the present analysis demonstrates potential decision-support value but does not directly measure reductions in maintenance expenditure, production losses, or intervention frequency. Such economic benefits would require prospective validation under real operating conditions.

CONCLUSIONS

This study developed a Financial-Risk Aware Digital Twin framework that integrates probabilistic industrial anomaly detection with an economic decision layer. Using the benchmark 3W dataset, an XGBoost-based multiclass classifier was applied to eight operational states and achieved an overall classification accuracy of 93%, with weighted-average precision and F1-score of 0.94 and 0.93, respectively. The analysis further demonstrated that statistical characteristics derived from pressure and temperature signals provide useful information for distinguishing normal and undesirable operational conditions.

The principal contribution of the proposed framework is the translation of predicted event probabilities into class-specific expected financial exposure. Under the illustrative economic scenarios evaluated in this study, identical predicted probabilities resulted in substantially different financial exposures for severe slugging, DHSV closure, and hydrate formation. The risk re-ranking example further demonstrated that the event with the highest predicted probability is not necessarily the event with the greatest economic consequence.

The economic intervention analysis produced a base-case hydrate break-even probability of 0.5% under an assumed $1,000,000 failure consequence and $5,000 preventive-action cost. Sensitivity analysis across alternative financial assumptions resulted in thresholds ranging from 0.125% to 2.0%, indicating that the central decision logic remained consistent despite substantial variation in the assumed costs. These results demonstrate the potential value of separating anomaly classification from downstream economic prioritization so that operator-specific financial information can be incorporated without changing the underlying diagnostic model.

The monetary values used in this study should be interpreted as illustrative scenario inputs rather than standardized industry costs. In addition, rare-event sample sizes and the absence of probability-calibration and prospective field-economic validation limit the extent to which the present findings can be generalized to operational deployment. Future work should therefore focus on probability calibration, larger validation samples for rare failure modes, asset-specific financial consequence estimation, and prospective evaluation of the framework using real-time industrial data.

AUTHOR CONTRIBUTIONS

Conceptualization, H.A.; methodology, H.A.; software, H.A.; formal analysis, H.A.; investigation, H.A.; data curation, H.A.; visualization, H.A.; writing—original draft, H.A.; writing—review and editing, H.A. The author has read and approved the final manuscript.

CONFLICTS OF INTEREST

The author declares no conflicts of interest.

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DATA AVAILABILITY

The data analyzed in this study are publicly available through the 3W Dataset. The dataset is available from Mendeley Data, Version 1, at https://doi.org/10.17632/r7774rwc7v.1

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The potential of electric bus integration in Baku's public transport system for carbon emission reduction and air quality improvement

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ABSTRACT

Electrification of bus fleets is increasingly used to decarbonize urban mobility, but its environmental performance depends on local fleet structure, operational intensity, electricity generation, and charging capacity. This study evaluates the potential of electric-bus integration in Baku, Azerbaijan, using official transport data for 2024–2026, a scenario-based direct CO_2 model, and a qualitative assessment of local air-quality co-benefits. As of March 2026, the Azerbaijan Land Transport Agency reported that nearly 2,300 buses operated daily in Baku and that 368 electric buses were present in the city fleet, equivalent to about 16% of the daily operating stock. The new Albalılıq depot provides service capacity for 167 battery-electric buses and includes 42 chargers rated at 240 kW. Under an illustrative diesel-displacement assumption of 225 km per bus per day, 0.35 L/km fuel consumption, and 2.68 kg CO_2/L, one conventional bus produces about 77.0 t CO_2 per year at the tailpipe. Replacing 100 buses therefore avoids about 7,703 t CO_2 annually, while 368 buses correspond to about 28,348 t. If the announced additional 169 electric buses are introduced, the illustrative avoided direct emissions rise to about 41,367 t per year. These estimates exclude electricity-generation and lifecycle emissions; therefore, net climate benefits depend on the carbon intensity of charging. The results support phased electrification combined with route prioritization, charging-network planning, and progressive power-sector decarbonization.

INTRODUCTION

Urban transport is a major source of energy demand and greenhouse-gas emissions, particularly in large metropolitan areas where population growth, motorization, and rising travel demand place sustained pressure on road networks. Public transport electrification has therefore become an important component of urban decarbonization strategies. Battery-electric buses (BEBs) are especially relevant because they combine high annual vehicle-kilometres with zero tailpipe emissions during operation, allowing climate and local air-quality benefits to be concentrated on frequently travelled urban corridors (IPCC, 2022; IEA, 2025).

Baku is Azerbaijan's largest urban and economic centre and depends heavily on road-based mobility. The city's bus network is one of the main pillars of public transport, but the historical reliance on diesel and compressed natural gas (CNG) vehicles has created an environmental challenge alongside congestion and growing private-car use. The National Transport Bulletin documented the expansion of motorization in Baku and the need to modernize the bus system through fleet renewal, route optimization, cleaner fuels, and digital management (Azerbaijan Land Transport Agency [AYNA], 2024a).

The transition has accelerated since 2024. AYNA reported the arrival of 160 electric buses for Baku during the COP29 period and their integration into the agency's monitoring system (AYNA, 2024b). By 5 March 2026, nearly 2,300 buses were operating daily on Baku routes and the city fleet included 368 electric buses. The Albalılıq electric-bus depot was also commissioned with 42 chargers rated at 240 kW and service facilities for 167 locally produced BYD battery-electric buses; a further 169 electric buses were planned for procurement during 2026 (AYNA, 2026). These developments mean that electric-bus integration in Baku is no longer only a pilot concept but an ongoing fleet-transition process.

Nevertheless, the environmental effect of electrification cannot be represented by tailpipe emissions alone. Electric buses remove direct exhaust CO_2, NOx and combustion-related particulate emissions from the street, but their net greenhouse-gas performance depends on electricity generation, vehicle energy consumption, battery production, charger utilization, route conditions and fleet scheduling. Azerbaijan's electricity system remains predominantly thermal: official 2025 statistics reported 24.82 TWh of generation from thermal power plants out of 28.66 TWh total generation, or approximately 86.6% (Ministry of Energy of Azerbaijan, 2026). Consequently, a robust assessment for Baku must distinguish direct urban emissions from upstream electricity-related emissions.

This study expands and updates the preliminary conference assessment presented at GCGW-2026 by incorporating 2026 fleet and charging-infrastructure information and by formalizing a set of policy-relevant electrification scenarios. The objectives are to: (i) describe the recent scale of electric-bus deployment in Baku; (ii) estimate the illustrative direct CO_2 emissions that can be avoided under different replacement scenarios; (iii) discuss the likely air-quality co-benefits; and (iv) identify the infrastructure and analytical conditions required for a deeper transition toward low-carbon public transport.

LITERATURE REVIEW

Environmental performance of electric buses

The literature consistently shows that electric buses can reduce operational greenhouse-gas emissions relative to conventional diesel buses, but the magnitude of the benefit is highly sensitive to the electricity mix and the chosen system boundary. Lajunen and Lipman (2016) showed that fully electric transit buses can substantially reduce CO_2 emissions while emphasizing the importance of operating conditions and lifecycle costs. Nordelöf et al. (2019) similarly found that the climate advantage of chargeable buses varies with grid carbon intensity and that all-electric buses provide particularly strong potential for reducing local air-pollution impacts. At city scale, Mao et al. (2021) demonstrated that real-world operating data and route conditions materially affect comparisons between battery-electric and diesel buses.

These findings are important for Baku because the electricity system is still dominated by thermal generation. A tailpipe-only assessment therefore represents the upper bound of direct urban emission reduction rather than a full lifecycle estimate. At the same time, the electricity mix is not static: expansion of renewable electricity can improve the climate performance of an already electrified bus fleet without replacing the vehicles themselves. This interaction between transport electrification and power-sector decarbonization is one of the principal reasons that scenario analysis is more informative than a single fixed emission value (IEA, 2025).

Operational planning, charging and air-quality co-benefits

Fleet electrification also creates operational constraints that are less significant for conventional buses. Battery capacity, charger power, depot location, charging windows, route length and vehicle scheduling must be coordinated to maintain service reliability. Dirks et al. (2022) showed that electric-bus integration is fundamentally a network-planning problem in which charging infrastructure and fleet transformation should be optimized together. Lee et al. (2023) likewise found that charger sharing, battery sizing, energy-consumption uncertainty and service-level requirements influence both environmental and economic outcomes. These studies suggest that the number of electric buses alone is an incomplete indicator of transition quality.

Local air quality provides an additional rationale for electrification. Battery-electric buses have no exhaust pipe and therefore eliminate direct combustion-related NOx and exhaust particulate emissions during operation. This can be particularly valuable on congested routes, at interchanges and in densely populated corridors where repeated acceleration, idling and braking increase exposure. However, non-exhaust particulate matter from tyres, brakes and road dust remains, meaning that electric buses should be treated as an important air-quality measure rather than a complete solution to urban particulate pollution (WHO, 2021).

For Baku, the research gap is therefore twofold. First, the rapid increase in the actual electric-bus fleet requires an updated baseline beyond the original pilot-oriented assessment. Second, local decision-making needs a transparent distinction between direct tailpipe reductions, electricity-related emissions and operational feasibility. The present study addresses this gap using official fleet data and a reproducible scenario framework rather than claiming a complete lifecycle inventory.

MATERIALS AND METHODS

Study design and data sources

The study uses a secondary-data, scenario-based research design. Official transport information from AYNA provides the fleet baseline, the number of electric buses, selected operating parameters, and charging-infrastructure developments. National electricity-generation statistics are used to interpret the relevance of indirect emissions. International sources from the IPCC, IEA and WHO support the climate, electrification and air-quality framework, while peer-reviewed studies are used to benchmark methodological choices.

Table 1 summarizes the principal data inputs. The analysis focuses on operational CO_2 emissions and does not attempt to quantify vehicle-manufacturing, battery-production, infrastructure-construction or end-of-life impacts. This boundary is deliberately retained because locally verified lifecycle inventory data for the Baku electric-bus fleet are not yet publicly available.

Table 1. Main indicators and sources used in the assessment

Indicator	Value / source
Daily bus fleet	~2,300 buses in Baku (Mar. 2026); AYNA (2026)
Electric-bus stock	368 buses; +169 planned; AYNA (2026)
Electric-bus operation	225 km/day illustrative mileage; AYNA (2024a)
Diesel parameters	0.35 L/km; 2.68 kg CO_2/L; AYNA (2024a)
Charging infrastructure	42 chargers × 240 kW at Albalılıq; AYNA (2026)
Electricity context	Thermal generation dominant in 2025; Ministry of Energy (2026)

The 225 km/day mileage, 0.35 L/km diesel consumption and 2.68 kg CO_2/L emission factor are retained from the preliminary conference model to ensure comparability. They are treated as illustrative assumptions rather than a verified average for every route and vehicle in the 2026 fleet.

Emission equations and scenario design

Annual direct CO_2 emissions from a conventional diesel bus are estimated using Equation (1), where N is the number of buses, D is the annual distance travelled per bus, FC is diesel fuel consumption per kilometre and EFfuel is the fuel-specific CO_2 emission factor.

$$Econv = N \times D \times FC \times EFfuel \quad (1)$$

For an electric bus, direct tailpipe CO_2 emissions are zero, but indirect operational emissions can be represented by Equation (2), where EC is electricity consumption per kilometre and EFelectricity is the emission factor of the electricity used for charging.

$$Eelectric = N \times D \times EC \times EFelectricity \quad (2)$$

Because verified route-level electricity consumption and a fleet-specific charging emission factor were not available, Equation (2) is not used to calculate a single net value. Instead, the study reports avoided direct tailpipe emissions using Equation (3) and interprets the electricity-generation context separately.

$$ERdirect = Ebaseline,diesel - Eafter\ replacement,direct \quad (3)$$

The scenario set includes: 100 buses, corresponding to the original conference-scale scenario; 160 buses, corresponding to the first major deployment reported in 2024; 368 buses, corresponding to the March 2026 electric-bus stock; 537 buses, representing the 368 existing buses plus 169 additional units planned for 2026; 1,150 buses, representing 50% of the approximately 2,300 daily bus fleet; and 2,300 buses, representing a theoretical full-fleet direct-emission boundary. In all scenarios, the replaced vehicle is treated as a diesel bus under the common operating assumptions. This produces an upper-bound estimate of avoided direct CO_2 where some real replacements may instead displace CNG buses.

The analytical sequence used to connect official data, emission calculations and interpretation is illustrated in Figure 1.

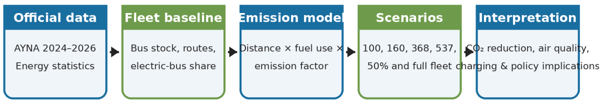

Figure 1. Analytical framework for assessing electric-bus integration in Baku. Source: authors' design.

RESULTS AND DISCUSSION

Recent scale of bus electrification in Baku

The 2026 baseline indicates a rapid shift from pilot activity toward material fleet penetration. With 368 electric buses among approximately 2,300 buses operating daily, electric vehicles represented about 16.0% of the daily bus stock in March 2026. If the announced additional 169 electric buses are added while the fleet size remains broadly unchanged, the share would rise to about 23.3%. This is a substantial change from the 2024 stage, when 160 electric buses were reported as a major new deployment for the city (AYNA, 2024b; AYNA, 2026).

Infrastructure development has advanced in parallel. The Albalılıq depot contains 42 chargers rated at 240 kW for a service group of 167 battery-electric buses, equivalent to almost four buses per installed charger. The combined charger nameplate capacity is 10.08 MW if all units operate simultaneously at rated power. Actual electricity demand will depend on charging schedules, state of charge, charging curves and simultaneous use; nevertheless, the scale of the installation demonstrates that depot-level grid planning is already becoming a significant component of Baku's transport system.

The evolution also has a green-economy dimension. The 167 buses assigned to Albalılıq were reported as produced in Azerbaijan, while the depot combines charging, washing, maintenance and operational functions. This suggests that fleet electrification can support domestic industrial capability and service employment in addition to environmental objectives, although a full economic impact or total-cost-of-ownership assessment falls outside the present study.

Table 2. Selected indicators of Baku's electric-bus transition, 2024–2026

Indicator	Reported status
Major 2024 deployment	160 electric buses
Daily buses in Baku, Mar. 2026	~2,300
Electric buses, Mar. 2026	368 (~16.0%)
Albalılıq depot	167 BEBs; 42 × 240 kW chargers
Additional buses planned in 2026	169
Potential stock after addition	537 (~23.3% if fleet size is unchanged)

The figures in Table 2 show that the policy question has shifted from whether electric buses can be introduced to how quickly the system can scale them while maintaining service quality, charging reliability and cost control.

Direct CO_2 reduction potential

Under the common assumptions, a diesel bus travelling 225 km/day covers 82,125 km annually. At 0.35 L/km, annual diesel use is approximately 28,744 L. Multiplying this by 2.68 kg CO_2/L gives about 77.03 t CO_2 per bus per year as direct tailpipe emissions. The result provides a transparent scaling factor for the electrification scenarios.

Table 3 shows the corresponding avoided direct emissions if electric buses replace diesel buses with the same annual mileage. The original 100-bus scenario avoids approximately 7,703 t CO_2/year. The 160-bus 2024 deployment corresponds to about 12,325 t/year, while the 368-bus March 2026 stock corresponds to about 28,348 t/year. A 537-bus stock, combining the March fleet with the announced additional 169 vehicles, would raise the illustrative direct reduction to about 41,367 t/year. At the theoretical boundary, electrifying half of the 2,300-bus daily fleet would avoid about 88,588 t/year and full diesel-equivalent replacement would avoid about 177,176 t/year.

Table 3. Illustrative avoided direct CO_2 emissions under electric-bus replacement scenarios

Scenario	Electric buses	Avoided direct CO_2 (t/year)
Initial scale	100	7,703
2024 deployment	160	12,325
Mar. 2026 stock	368	28,348
Stock + planned 169	537	41,367
50% of daily fleet	1,150	88,588
Full daily fleet boundary	2,300	177,176

These values should be interpreted as avoided direct tailpipe emissions, not as net lifecycle reductions. They assume diesel displacement, constant daily mileage throughout the year and identical operation across scenarios. If electric buses replace CNG buses, if actual mileage is lower, or if charging electricity has high carbon intensity, the net greenhouse-gas benefit will be smaller than the direct values shown above.

Electricity mix and the importance of net-emission accounting

The electricity system is central to the interpretation of the results. Official statistics for 2025 reported 28.66 TWh of electricity generation in Azerbaijan, of which 24.82 TWh was generated at thermal power plants. Although renewable generation is increasing, the continuing dominance of thermal generation means that electric-bus charging still has associated upstream CO_2 emissions (Ministry of Energy of Azerbaijan, 2026). The direct reductions in Table 3 therefore describe the urban tailpipe benefit and the maximum operational displacement before electricity-related emissions are deducted.

This distinction is consistent with the wider literature. Nordelöf et al. (2019) showed that the lifecycle ranking of electric and combustion buses changes with electricity carbon intensity, while Mao et al. (2021) emphasized the need to use real operational data when estimating city-scale benefits. For Baku, future work should therefore collect route-specific BEB electricity use in kWh/km and combine it with an annually updated or marginal grid emission factor. Such data would allow Equation (2) to be applied and would convert the present direct-emission analysis into a well-to-wheel or lifecycle assessment.

The same logic creates a dynamic policy advantage: once buses are electrified, power-sector decarbonization automatically improves their operational carbon performance. In contrast, the emission intensity of a diesel bus cannot fall substantially without changing the fuel or the vehicle. This strengthens the case for coordinating transport electrification with renewable-power expansion rather than evaluating the two sectors independently.

Air-quality benefits and route prioritization

Electric buses also provide local environmental benefits that are not captured by the CO_2 calculations. Zero tailpipe operation removes direct exhaust NOx and combustion-derived particulate emissions from the street environment. This is especially relevant around transport hubs, schools, hospitals, dense residential corridors and heavily trafficked streets where exposure is concentrated. WHO (2021) identifies $PM_{2.5}$, PM_{10} and NO_2 among the key pollutants associated with adverse health outcomes, giving local air-quality improvement an independent policy value beyond climate mitigation.

The air-quality benefit is not equivalent to eliminating all transport-related particulate matter. Tyre wear, road abrasion and resuspended dust remain, while electricity generation can transfer some emissions away from the point of use. Nevertheless, moving exhaust emissions away from densely populated urban corridors can improve exposure conditions. An optimization-oriented deployment strategy would therefore prioritize routes using three combined criteria: high daily kilometres, high passenger demand and high population exposure. Such prioritization can maximize avoided emissions per vehicle and improve the social return on limited charging and fleet investment.

The photographic example in Figure 2 illustrates the type of battery-electric buses being incorporated into Azerbaijan's sustainable-transport transition.

Figure 2. Electric buses in Azerbaijan. Source: Trend News Agency (2026).

Implementation implications and limitations

The main implementation implication is that fleet procurement, route allocation and charging infrastructure must be planned as one system. The Albalılıq depot demonstrates the importance of high-capacity charging, but further electrification will require additional depot capacity, electricity-network connections, maintenance skills, spare-part supply and operational data. International studies indicate that charger sharing and coordinated scheduling can materially influence cost and feasibility, while energy-consumption uncertainty should be incorporated into fleet planning (Dirks et al., 2022; Lee et al., 2023).

The study has several limitations. First, the direct CO_2 calculations use common assumptions derived from the preliminary assessment rather than route-level fuel records for each bus. Second, the scenarios treat all displaced conventional buses as diesel, although Baku also operates CNG buses; this makes the direct reduction values an upper-bound diesel-equivalent comparison. Third, electric-bus energy consumption in kWh/km, battery degradation, seasonal auxiliary loads and charging losses are not quantified. Fourth, the analysis does not include vehicle and battery manufacturing, end-of-life impacts, capital costs or maintenance savings. Finally, local $PM_{2.5}$, PM_{10} and NOx improvements are discussed qualitatively because paired route-level concentration data before and after electric-bus deployment are not yet available.

These limitations define a clear research agenda. A next-stage study should integrate telematics from electric and conventional buses, route-specific passenger loads, measured energy use, charger utilization, local electricity emission factors and roadside air-quality monitoring. A total-cost-of-ownership module could then be added to identify the routes and fleet-renewal sequence that jointly minimize emissions and system cost.

CONCLUSIONS

Baku's bus electrification has progressed rapidly from an early pilot concept to a material component of the city's public-transport fleet. Official data indicate that by March 2026 the city had approximately 368 electric buses within a daily operating fleet of nearly 2,300 vehicles, while new depot infrastructure provided 42 high-power chargers and service capacity for 167 battery-electric buses. An additional 169 buses planned for 2026 would, if added without a large change in total fleet size, raise the electric share from about 16.0% to approximately 23.3%.

Using the study's illustrative diesel-displacement assumptions, each replaced conventional bus corresponds to about 77.03 t CO_2/year of avoided direct tailpipe emissions. This gives approximately 28,348 t/year for 368 buses and about 41,367 t/year for a 537-bus stock. These values are not net lifecycle reductions: the climate performance of electric buses also depends on electricity generation, charging losses, vehicle efficiency and battery-related impacts. The predominance of thermal electricity generation in Azerbaijan makes power-sector decarbonization an important complement to transport electrification.

The strongest near-term strategy is therefore a phased and data-driven transition. Electric buses should be prioritized on high-mileage and high-exposure routes, charging infrastructure should expand in parallel with fleet procurement, and operational data should be used to optimize charger use and route scheduling. With these conditions, electric buses can contribute simultaneously to lower urban tailpipe emissions, improved local air quality, reduced fossil-fuel dependence and the modernization of Baku's public-transport system.

AUTHOR CONTRIBUTIONS

Conceptualization, N.Q. and U.M.; methodology, N.Q. and U.M.; formal analysis, U..M, E.H..; data curation, U.M.; writing—original draft, U.M.; writing—review and editing, N.Q. and U.M. All authors have read and agreed to the final manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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DATA AVAILABILITY

The study is based on publicly available reports and webpages cited in the reference list. The scenario calculations and assumptions are fully reported in the manuscript.

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Landscape and meteorological drivers of desertification in Shaki district, Azerbaijan

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ABSTRACT

Desertification is one of the major environmental challenges affecting land resources in arid and semi-arid regions. This study evaluates desertification processes in the Shaki District of Azerbaijan during 2021–2025 using an integrated landscape and meteorological approach. The assessment was based on meteorological observations, including air temperature, relative humidity, and atmospheric circulation patterns, combined with field investigations of soil conditions and vegetation indicators. The results show that desertification is mainly associated with persistent atmospheric dryness, characterised by an average annual relative humidity of 46–50%, high summer air temperatures (30–40°C), and variable air mass circulation. Although meteorological data for 2024–2025 indicate a slight increase in relative humidity, field observations reveal that land degradation remains active, as evidenced by soil erosion, denudation features, and the expansion of xerophytic vegetation. The study demonstrates that combining meteorological monitoring with landscape observations provides an effective framework for assessing desertification at the regional scale. The findings contribute to environmental monitoring and support sustainable land management and climate adaptation strategies in the Shaki District.

INTRODUCTION

Desertification is one of the most serious environmental challenges affecting land resources in arid and semi-arid regions worldwide. It is closely associated with climate change, land degradation, and alterations in hydrological processes. Rising air temperatures, irregular precipitation patterns, and declining atmospheric humidity accelerate soil degradation, reduce vegetation cover, and impair ecosystem productivity. These processes threaten environmental sustainability, agricultural production, and the provision of ecosystem services, particularly in regions that are highly sensitive to climate variability (UNCCD, 2022; IPCC, 2023; Prăvălie, 2021).

Azerbaijan is among the countries where desertification has become an important environmental issue due to its diverse climatic conditions and increasing anthropogenic pressure on natural ecosystems. The Shaki–Zagatala region, located on the southern slopes of the Greater Caucasus, is particularly vulnerable because of its complex topography, heterogeneous landscapes, and pronounced climatic contrasts. Previous studies have reported increasing risks of land degradation in this region under the combined influence of climatic variability and human activities (Regional Geographic Problems of the Republic of Azerbaijan, 1999; Gahramanov et al., 2023; Mustafabeyli et al., 2022).

Therefore, the present study aims to evaluate desertification processes in the Shaki District during the period 2021–2025 by integrating meteorological observations with landscape monitoring. Particular attention is given to temporal variations in relative humidity and their relationship with observed indicators of land degradation.

To achieve this objective, meteorological observations were integrated with field investigations of soil conditions and vegetation characteristics to evaluate current desertification trends. This integrated approach provides updated information on recent environmental changes in the Shaki District and contributes to regional environmental monitoring, sustainable land management, and climate change adaptation strategies. The results are expected to support evidence-based decision-making for the sustainable management of vulnerable landscapes in northwestern Azerbaijan.

LITERATURE REVIEW

Desertification is widely recognized as a complex process resulting from the interaction of climatic variability, land-use pressures, soil degradation, vegetation loss, and changes in hydrological conditions. Previous studies have shown that climate change can intensify land degradation through increasing air temperatures, changes in precipitation patterns, more frequent droughts, and increased atmospheric water demand. These processes can reduce soil moisture availability, increase evapotranspiration, and weaken the resilience of terrestrial ecosystems, particularly in regions experiencing increasing climatic aridity (IPCC, 2019; UNCCD, 2022; Prăvălie, 2021).

Climatic conditions are therefore important components in the assessment of desertification and land degradation. Temperature and precipitation are among the most frequently analyzed climatic variables, whereas relative humidity has received comparatively less attention as an independent indicator. Atmospheric humidity is closely related to evapotranspiration, soil-water balance, plant water availability, and vegetation dynamics. Prolonged periods of low relative humidity, particularly when combined with high temperatures and insufficient precipitation, can increase atmospheric evaporative demand and contribute to the drying of soils and vegetation. Consequently, variations in relative humidity may provide additional information for assessing climatic conditions associated with land degradation and ecosystem stress (IPCC, 2019; Prăvălie, 2021; UNCCD, 2022).

In Azerbaijan, desertification and land degradation have been associated with climatic variability, increasing temperatures, changes in precipitation regimes, and anthropogenic pressure on natural ecosystems. The country's considerable climatic and topographic diversity results in substantial spatial differences in the intensity and distribution of land degradation processes. Previous studies have emphasized the importance of climate-related factors in determining the vulnerability of different landscapes to degradation and desertification.

The southern slopes of the Greater Caucasus, including the Shaki–Zagatala region, are particularly important for the study of these processes because of their complex topography, pronounced vertical landscape differentiation, and strong climatic contrasts. Previous research in the region has examined soil characteristics, vegetation dynamics, landscape structure, and biogeochemical processes (Mustafabeyli and Gahramanov, 2023), for example, associated desertification-related processes in the Shaki–Zagatala region with climatic changes, relief conditions, and changes in biological productivity. Their findings also demonstrated differences in biogeochemical characteristics among landscape belts, highlighting the importance of landscape differentiation in the assessment of environmental degradation.

Other regional studies have identified climate variability, anthropogenic pressure, soil erosion, and vegetation degradation as important factors influencing the development of desertification processes in the Shaki–Zagatala region. These studies indicate that the assessment of desertification requires an integrated approach that considers climatic conditions together with landscape, soil, and vegetation characteristics. Such an approach is particularly relevant in mountainous and foothill environments, where climatic conditions and landscape properties can vary substantially over relatively short distances.

Research focusing specifically on the Shaki District has likewise highlighted the importance of climatic and environmental conditions in determining the characteristics and stability of local landscape systems. The complex climatic structure of the southern slopes of the Greater Caucasus produces considerable spatial and temporal variation in temperature, precipitation, evaporation, and relative humidity. These climatic variations interact with relief, soil properties, and vegetation characteristics and may influence the susceptibility of individual landscapes to degradation.

Despite the contributions of previous studies, the role of relative humidity in relation to recent desertification processes remains comparatively underexplored at the district level in Azerbaijan. Existing research has generally focused on temperature, precipitation, drought, soil degradation, vegetation change, and broader indicators of climatic aridity. Limited attention has been given to the combined assessment of relative humidity and landscape indicators over a recent multi-year period, particularly in the Shaki District. Addressing this gap, the present study examines meteorological variations during 2021–2025 together with field observations of soil and vegetation conditions. Particular attention is given to temporal variations in relative humidity and their relationship with observed indicators of land degradation, providing an integrated perspective on recent desertification processes in the Shaki District.

MATERIALS AND METHODS

Study Area

The study was conducted within the administrative boundaries of the Shaki District, located in northwestern Azerbaijan on the southern slopes of the Greater Caucasus Mountains (Fig. 1). The central part of the district is situated at elevations ranging from approximately 500 to 850 m above sea level (a.s.l.), while the northern mountainous area reaches elevations of up to 3683 m a.s.l. along the Main Caucasus Range. The study area is characterised by a complex topography and comprises three major physiographic units: (i) the Main Caucasus Range in the north, (ii) the Ganikh–Ayrichay intermontane valley in the central part, and (iii) the Ajinohur foothill zone in the south (Mustafabeyli & Gahramanov, 2023b; National Atlas of the Republic of Azerbaijan, 2014).

The climate of the study area is generally moderately warm, although climatic conditions vary considerably with altitude. The combination of mountainous terrain and atmospheric circulation patterns creates distinct local climatic conditions that influence soil moisture, vegetation distribution, and land degradation processes (Peel et al., 2007).

The soil cover exhibits pronounced vertical zonation and includes brown mountain-forest, dark brown mountain-forest, meadow-forest, and grey-brown soil types characteristic of the semi-arid areas in the south. The vegetation cover is mainly represented by broad-leaved mountain-forest formations, including oak, beech, hornbeam, and walnut forest groups, which are dominant in the forested landscapes (Mustafabeyli & Gahramanov, 2023b).

The combination of diverse topography, altitudinal climatic gradients, heterogeneous soil cover, and natural vegetation makes the Shaki District a suitable study area for investigating the relationships between climatic variability and desertification processes. These environmental characteristics provide favourable conditions for assessing the interaction between meteorological factors and landscape degradation under changing climatic conditions.

Research Objects and Monitoring Framework

The research focused on assessing desertification processes in the Shaki District through integrated geo-ecological monitoring of soil degradation, vegetation dynamics, and meteorological conditions during the period 2021–2025. The monitoring programme was designed to assess the spatial characteristics and intensity of land degradation and to evaluate the relationships between climatic variability and landscape changes, in accordance with general principles of environmental monitoring and land degradation assessment (UNCCD, 2022; FAO, 2021).

Field investigations were carried out in areas considered vulnerable to desertification within the Ganikh–Ayrichay Valley and the Ajinohur foothill zone, including the territories of Chaygaragoyunlu, Turan, Gayabashi, Boyuk Dehne, Kichik Dehne, Sarija, and Dashbulag villages. Surveys were conducted during periods of pronounced moisture deficiency, when the effects of reduced moisture availability on soil and vegetation were most evident. Particular attention was given to the occurrence and spatial distribution of xerophytic indicator species, soil erosion features, vegetation degradation, and other visible indicators of desertification (Mustafabeyli & Gahramanov, 2024).

Landscape assessment was based on the landscape classification principles proposed by Isachenko (1991), which classify landscapes according to the degree of anthropogenic transformation. Following this approach, the investigated landscapes were grouped into six categories: natural (unaltered) landscapes, slightly modified landscapes, moderately transformed landscapes, severely degraded landscapes, managed (cultural) landscapes, and artificial landscapes (Isachenko, 1991; Mustafabeyli, 2019).

The monitoring framework integrated field observations with meteorological data analysis and landscape classification to evaluate the spatial variability of desertification processes. This multidisciplinary approach is consistent with internationally recognised frameworks for land degradation assessment and provides a reliable basis for environmental monitoring, sustainable land management, and climate adaptation planning (UNCCD, 2022; FAO, 2021; Cowie et al., 2018).

Research Methods

The assessment of desertification processes in the Shaki District was based on an integrated methodological approach combining field investigations, laboratory analyses, landscape observations, and meteorological monitoring. The selected methods enabled the evaluation of both the natural and anthropogenic factors influencing land degradation.

Biogeochemical analysis was applied to determine the mineralogical composition and geochemical characteristics of soil, silt, and clay samples collected from representative landscape units. The analysis focused on identifying the distribution of major minerals and chemical components associated with desertification processes and landscape evolution (IUSS Working Group WRB, 2022; Mustafabeyli & Gahramanov, 2025).

Soil and sediment sampling was carried out at representative sites covering different geomorphological and landscape conditions. Samples of soil, alluvial sediments, and clay were collected according to standard field sampling procedures to evaluate the physical and mineralogical characteristics of the study area and to identify spatial patterns of land degradation (FAO, 2021).

Meteorological monitoring included the analysis of air temperature, relative humidity, precipitation, and atmospheric circulation during the period 2021–2025. Particular attention was paid to the annual frequency of days with relative humidity below 50% and 30%, as these conditions were considered indicators of increasing atmospheric dryness and desertification risk.

Bio-indicator monitoring consisted of repeated field observations of xerophytic vegetation together with the assessment of soil erosion, denudation features, shrub cover, and other visible indicators of landscape degradation. Photographic documentation was used to verify seasonal and interannual changes in vegetation and land surface conditions (Mustafabeyli & Gahramanov, 2024).

The collected field observations, laboratory results, and meteorological records were integrated to evaluate the spatial and temporal dynamics of desertification in the Shaki District. This multidisciplinary approach is consistent with internationally recognised principles of land degradation assessment and environmental monitoring (UNCCD, 2022; FAO, 2021).

Landscape Belts and Territorial Zoning

The landscape analysis was based on the altitudinal landscape classification developed by the Department of Landscape Studies for the Shaki District. According to this classification, the study area comprises six major landscape belts that reflect the combined influence of altitude, relief, climate, soils, and vegetation (Isachenko, 1991; Mustafabeyli & Gahramanov, 2022).

The identified landscape belts are:

- Subnival and nival landscapes of highly dissected high-mountain areas;
- Alpine, subalpine, and mountain meadow landscapes of highly dissected high-mountain zones;
- Mountain broad-leaved forest landscapes of steeply dissected middle-mountain areas;
- Forest-steppe landscapes of moderately dissected intermontane plains;
- Dry-steppe landscapes of moderately and strongly dissected foothill and low-mountain areas;
- Semi-desert landscapes of moderately and strongly dissected low-mountain terrains.

The spatial distribution of these landscape belts within the 2,432.8 km^2 territory of the Shaki District was determined using high-resolution satellite imagery available through Google Earth, supported by field observations and geomorphological analysis. Landscape boundaries were delineated by considering topographic characteristics, drainage networks, river valleys, ravines, slope morphology, and other physiographic features. This integrated approach enabled the preparation of a reliable landscape zoning scheme for the study area (Mustafabeyli & Gahramanov, 2022; FAO, 2021).

The proportional distribution of the landscape belts is as follows: subnival landscapes – 11%, alpine and subalpine meadows – 13%, mountain forests – 15%, forest-steppe landscapes – 10%, steppe and meadow-steppe landscapes – 24%, and semi-desert landscapes – 27%. The predominance of steppe and semi-desert landscapes indicates that a considerable part of the district is naturally susceptible to drought and land degradation, emphasizing the importance of continuous environmental monitoring and sustainable land management.

The landscape zoning established in this study served as the spatial framework for selecting monitoring sites and analysing the relationships between climatic variability, soil degradation, and desertification processes across the different landscape belts.

Meteorological Observations and Climatic Indicators

Daily meteorological observations were conducted to assess the climatic conditions associated with desertification in the Shaki District during the 2021–2025 study period. The analysed variables included air temperature, relative humidity, atmospheric pressure, wind direction, ultraviolet (UV) index, and atmospheric circulation patterns. These parameters were used to evaluate temporal climatic variability and its influence on desertification processes.

Meteorological data were obtained from the AccuWeather and GISMETEO online databases, which provided continuous daily observations throughout the monitoring period. To improve the reliability of the analysis, data from several meteorological stations within the Shaki–Zagatala region, including Zagatala, Shaki, Oguz, and Gabala, were incorporated into the study. In addition, observations from the Usukhchay meteorological station (Republic of Dagestan, Russian Federation) were included because of its strategic location for tracking approaching air masses before they reached the study area.

Comparative analysis of meteorological observations from the regional stations made it possible to identify the dominant directions of air-mass movement and evaluate their influence on temperature and humidity conditions in the Shaki District. The inclusion of the Usukhchay station improved the interpretation of synoptic processes by allowing earlier detection of cold continental and polar air masses moving from the north, northwest, and northeast, while warm tropical air masses generally approached the region from southern latitudes.

Previous investigations have shown that atmospheric circulation over the Shaki–Zagatala region is characterised by relatively frequent changes in air-mass direction, with approximately 15–18 circulation events per month (Mustafabeyli & Gahramanov, 2023a). Such variability reflects the interaction of air masses originating from different geographical regions and contributes to fluctuations in temperature and atmospheric humidity (Mustafabeyli & Gahramanov, 2025). These climatic variations are considered important factors influencing soil moisture conditions, vegetation dynamics, and the development of desertification processes in the study area.

Overall, the selected meteorological variables provide a reliable basis for evaluating the effects of climatic variability on land degradation and desertification processes and are widely recognised as key indicators in environmental monitoring (IPCC, 2023; WMO, 2023).

RESULTS AND DISCUSSION

Daily meteorological observations obtained from the AccuWeather and GISMETEO databases for the period 2021–2025 were analysed to evaluate the relationships between relative humidity, air temperature, wind conditions, and desertification processes in the Shaki District. The analysis revealed considerable interannual variability in the main climatic indicators, reflecting changes in atmospheric moisture conditions and their potential influence on landscape degradation.

Relative Humidity Dynamics

The analysis of relative humidity data for the period 2021–2025 revealed pronounced interannual variations in atmospheric dryness within the Shaki District (Table 1). The highest number of days with relative humidity below 30% was recorded in 2021 (76 days). This number decreased to 47 days in 2022, 38 days in 2023, and reached its minimum value of 25 days in 2024. However, in 2025, the number of low-humidity days increased again to 45, indicating renewed atmospheric drying.

The most pronounced dry conditions occurred during August 2021, when relative humidity remained below 30% for 23 days, resulting in a monthly average relative humidity of only 25%. Such conditions indicate exceptionally dry atmospheric conditions during the summer season and suggest an increased risk of soil moisture depletion and vegetation stress.

Extended periods of low atmospheric humidity are generally associated with reduced soil moisture availability, deterioration of vegetation cover, and increased susceptibility to wind erosion. The exceptionally dry conditions recorded in 2021 therefore represent the period with the highest potential desertification risk within the five-year observation period. Although atmospheric humidity generally improved during 2022–2024, the increase in the number of dry days observed in 2025 suggests that climatic variability remains an important factor influencing desertification processes in the study area. To facilitate comparison of monthly humidity conditions during the monitoring period, the maximum and minimum monthly relative humidity values recorded between 2021 and 2025 are presented in Table 1.

Table 1. Mean monthly relative humidity values (%) in the Shaki district during the 2021–2025 period.

Years	2021		2022		2023		2024		2025	
Months	**max**	**min**	**max**	**min**	**max**	**min**	**max**	**min**	**max**	**min**
January	80	40	76	45	82	61	86	62	86	58
February	78	50	79	52	80	58	79	61	93	67
March	83	53	84	62	80	52	84	62	79	50
April	75	45	74	47	82	50	78	49	82	57
May	75	50	85	57	81	51	84	55	79	52
June	61	37	75	46	79	49	75	45	74	46
July	70	44	62	36	72	41	73	44	63	34
August	50	25	59	31	66	37	73	42	65	34
September	72	46	71	43	82	56	73	39	80	53
October	86	64	81	52	79	49	85	57	84	56
November	83	59	79	55	75	44	84	56	83	54
December	78	44	90	68	83	57	84	59	91	64
Annual Mean	**74**	**46**	**76**	**50**	**78**	**50**	**80**	**53**	**80**	**52**

As shown in Table 1, the multi-year mean annual relative humidity in the Shaki District remained close to the 50% threshold throughout the monitoring period. Relative humidity below 30% is generally considered an indicator of severe atmospheric dryness, while long-term annual averages below 50% may contribute to reduced soil moisture availability, vegetation stress, and an increased risk of land degradation (UNCCD, 2022; IPCC, 2023).

The lowest annual mean relative humidity (46%) was recorded in 2021, indicating the driest atmospheric conditions observed during the five-year monitoring period. Annual mean values remained close to 50% in 2022 and 2023, suggesting that dry climatic conditions continued to influence the study area despite moderate year-to-year fluctuations.

Although the mean annual relative humidity increased slightly during 2024–2025 compared with the 2021–2023 period, this improvement was relatively small and did not indicate a substantial recovery of environmental conditions. Field observations conducted during the same period continued to reveal signs of soil degradation, vegetation deterioration, and the expansion of xerophytic plant communities, suggesting that desertification processes remain active within the study area.

Prevailing Wind Regimes and Atmospheric Dynamics

The analysis of prevailing wind directions and atmospheric circulation patterns was conducted to evaluate their potential influence on desertification processes in the Shaki District during the 2021–2025 monitoring period. Wind is an important climatic factor affecting soil erosion, moisture transport, and the spatial distribution of land degradation, particularly in areas with heterogeneous topography (IPCC, 2023; WMO, 2023).

Daily observations obtained from the GISMETEO and AccuWeather databases showed considerable temporal variability in atmospheric circulation during the study period. The greatest fluctuations were recorded in 2022 and 2025, when the dominant wind direction changed between 7 and 22 times per month. Such frequent changes in air-mass movement indicate highly dynamic atmospheric conditions that may increase the susceptibility of exposed soils to wind erosion and enhance landscape instability.

The highest circulation variability was observed mainly during May, June, and October. These months represent transitional climatic periods, during which vegetation cover is relatively vulnerable and soil moisture conditions change rapidly. Consequently, frequent changes in wind direction during these seasons may contribute to increased soil erosion and facilitate the development of desertification processes.

Previous studies have demonstrated that atmospheric circulation over the Shaki–Zagatala region is considerably more variable than in many inland regions of Central Asia (Mustafabeyli & Gahramanov, 2025). While changes in dominant air-mass direction generally occur 4–5 times per month in Central Asia, they were observed 7–22 times per month in the Shaki District during the present study. This difference is primarily related to the complex mountainous topography of the Greater Caucasus, which influences local atmospheric circulation and increases climatic variability.

Based on the five-year monitoring period, the dominant wind directions of the Shaki District were identified and used to characterise the regional wind regime. The results provide important information for understanding the relationships between atmospheric circulation, soil erosion, and desertification processes. The distribution of prevailing wind directions during the 2021–2025 period is presented in Table 2.

Table 2. Prevailing monthly wind directions based on the number of recorded days in the Shaki district (2021–2025).

Months	2021 (Days)	2022 (Days)	2023 (Days)	2024 (Days)	2025 (Days)
January	East (10)	North-West (19)	North-East (11)	South (7)	North-East (9)
February	South-East (6)	North-West (9)	North-West (7)	South-West (10)	South (7)
March	North-East (7)	North-West (8)	North-West (10)	South (13)	North-East (9)
April	East (10)	Local winds (12)	North (6)	South-West (7)	South-West (6)
May	East (7)	North-East (7)	North-East (10)	South (12)	North-West (11)
June	South (7)	South (6)	North-East (10)	South (10)	North-East (9)
July	South (7)	North-East (6)	North-East (9)	North-East (9)	North-East (8)
August	South-East (12)	South-East (14)	West (11)	South (10)	North-East (6)
September	South-West (8)	North-East (9)	North-East (9)	North-East (7)	West (11)
October	East (6)	North-West (6)	North-West (14)	North-East (7)	North-West (11)
November	South-East (7)	North-West (10)	North-West (11)	North-East (6)	North-East (15)
December	North-West (9)	North-East (9)	North-West (13)	West (8)	North-West (10)

According to the meteorological observations for the 2021–2025 period, both the prevailing wind directions and the frequency of wind events exhibited considerable seasonal and interannual variability. During the winter months, the wind regime was dominated mainly by northerly (N) and southerly (S) air flows, whereas the summer season was characterised primarily by north-easterly (NE) and southerly (S) winds.

Several interannual anomalies were also identified during the monitoring period. For example, the north-west (NW) wind direction was recorded for 19 days in January 2022, indicating an unusual atmospheric circulation pattern for that month. Such anomalies reflect the dynamic nature of regional atmospheric circulation and the influence of changing synoptic conditions on local weather patterns.

The observed seasonal and interannual variations in prevailing wind directions provide important information for understanding atmospheric circulation over the Shaki District. These variations influence the transport of air masses, moisture distribution, and local climatic conditions and may contribute to differences in the intensity and spatial distribution of desertification processes.

Temperature Profiles and Thermal Regimes

Air temperature is one of the principal climatic factors influencing desertification processes. High temperatures increase evapotranspiration, reduce soil moisture, and intensify water stress in vegetation. Prolonged periods of elevated temperature may therefore contribute to soil degradation, reduced vegetation cover, and an increased risk of desertification, particularly in arid and semi-arid environments (IPCC, 2023; UNCCD, 2022).

In this study, daily minimum and maximum air temperatures recorded in the Shaki District during the 2021–2025 period were obtained from the GISMETEO and AccuWeather meteorological databases. The collected data were analysed to evaluate seasonal and interannual variations in temperature and to identify periods characterised by exceptionally high thermal conditions.

The analysis revealed clear seasonal temperature fluctuations, with the highest temperatures occurring during the summer months and the lowest values recorded in winter. These observations provide an important basis for assessing the influence of the regional thermal regime on soil moisture conditions and the development of desertification processes.

The annual minimum and maximum air temperatures recorded during the 2021–2025 monitoring period are presented in Table 3.

Table 3. Mean monthly temperature values (°C) in the Shaki district during the 2021–2025 period.

Years	2021		2022		2023		2024		2025	
Months	**min**	**max**	**min**	**max**	**min**	**max**	**min**	**max**	**min**	**max**
January	-2	9	1	10	-2	7	2	9	1	10
February	2	12	2	13	0	8	3	11	2	7
March	2	12	1	11	4	8	5	14	5	17
April	12	23	10	22	7	18	12	23	10	19
May	15	26	12	23	13	25	13	23	15	25
June	20	32	19	30	17	30	19	31	17	28
July	22	33	21	32	20	32	21	31	21	33
August	23	35	22	34	19	32	21	32	22	33
September	16	26	17	29	16	27	16	28	16	27
October	9	17	13	22	10	19	11	21	12	22
November	6	15	7	16	4	12	5	14	7	18
December	3	11	1	7	0	8	1	9	2	10
Annual Mean	**11**	**21**	**11**	**21**	**9**	**19**	**11**	**21**	**11**	**21**

According to the temperature data presented in Table 3, the mean annual minimum temperature in the Shaki District varied between 9°C and 11°C, while the mean annual maximum temperature ranged from 19°C to 21°C during the 2021–2025 monitoring period. The five-year average was 10.6°C for the annual minimum temperature and 20.6°C for the annual maximum temperature.

The lowest temperatures were consistently recorded during January and February, reaching −2°C in 2021 and 2023. In contrast, the highest temperatures occurred during July and August, with an absolute maximum of 35°C recorded in 2021.

Among the monitored years, 2023 was characterised by relatively lower temperatures, with an annual mean minimum of 9°C and a mean maximum of 19°C, whereas the remaining years exhibited relatively stable thermal conditions, with average minimum and maximum temperatures close to 11°C and 21°C, respectively.

The results indicate clear seasonal and interannual variability in air temperature. High summer temperatures increase evapotranspiration and reduce soil moisture availability, thereby creating favourable conditions for land degradation and desertification. In contrast, the relatively lower temperatures observed in 2023 suggest that climatic conditions may vary considerably between years, influencing the intensity of desertification processes.

Overall, the observed temperature regime confirms the temperate continental climatic characteristics of the Shaki District and highlights the important role of air temperature in controlling soil moisture conditions and landscape dynamics. No consistent long-term warming or cooling trend was identified during the 2021–2025 monitoring period. Nevertheless, the persistence of high summer temperatures, together with periods of low relative humidity, creates favourable conditions for soil moisture depletion and supports the continued development of desertification processes observed during field investigations.

Mineralogical Composition of Landscape Materials

The mineralogical composition of soil, silt, and clay samples was analysed to evaluate the geological characteristics of the study area and their relationship with landscape stability and desertification processes. Mineralogical analysis provides important information on the weathering resistance of parent materials, soil development, and the susceptibility of landscapes to erosion and land degradation.

Representative samples were collected from different landscape units within the Shaki District and analysed using mineralogical laboratory methods. The identified minerals were used to assess the dominant geological components and to evaluate their potential influence on soil properties and landscape evolution. The results of the mineralogical analysis are presented in Table 4.

Table 4. Mineralogical Composition (%) of Silt (1–5), Soil (6–9), and Clay (10–12) Samples within the Shaki District

Sample Classification / Designation	SiO2 (α-quartz)	Feldspar	CaCO3	Clinochlore	Illite
Ayrichay reservoir (Western section)	22	16	27	14	10
Ayrichay reservoir (Eastern section)	23	15	26	15	10
Ayrichay River (Qakh district area)	33	20	13	16	10
Alijanchay silt	20	14	25	25	9
Dahnachay silt	18	15	35	17	6
Mustafabey property (Soil sample)	32	21	15	13	11
Bash Shabalid (Middle mountain-forest)	45	12	-	25	10
Bash Shabalid (Low mountain-forest)	37	14	-	30	10
Bash Shabalid (Forest-steppe zone)	21	12	33	15	12
Shaki brick factory clay	20	12	26	22	12
Okhud brick factory clay	16	17	20	25	10
Gayabashi clay quarry	20	14	15	27	13

The mineralogical composition of the analysed silt, soil, and clay samples is presented in Table 4. Quartz (SiO_2) was the dominant mineral in the middle mountain-forest soils of Bash Shabalid, accounting for approximately 45% of the total mineral composition. The relatively high quartz content indicates the predominance of resistant silicate minerals within these landscape units.

Calcite ($CaCO_3$) was most abundant in the Dahnachay silt samples (35%) and in the forest-steppe soils of Bash Shabalid (33%), reflecting the widespread occurrence of carbonate-rich parent materials in the study area. Clay minerals, particularly clinochlore (up to 30%) and illite (6–13%), were also common in several samples, indicating the presence of weathered fine-grained sedimentary materials.

The mineralogical composition varied among the investigated landscape units. Compared with previous studies conducted in the neighbouring Qakh District, the analysed samples from the Shaki District generally contained lower proportions of quartz and feldspars and relatively higher contents of calcite and clinochlore (Mustafabeyli & Gahramanov, 2025). These differences are consistent with the geological characteristics of the study area, where carbonate sedimentary rocks are widespread.

The observed mineral assemblages may influence soil properties, including alkalinity, water retention, and susceptibility to erosion. Together with the meteorological conditions described above, these characteristics contribute to the spatial variability of desertification processes in the Shaki District.

Visual Monitoring of Desertification Dynamics and Landscape Transformations

Field surveys were conducted at representative sites within the Shaki District to document visible indicators of desertification and landscape change. Photographic observations were used to complement the meteorological, mineralogical, and field data by providing visual evidence of ongoing environmental changes.

The photographs illustrate several characteristic features of landscape degradation, including the expansion of xerophytic vegetation, changes in shrub density, increased weed (thistle) infestation in agricultural fields, and visible signs of soil erosion and surface denudation. These observations were recorded during repeated field visits and were compared with the meteorological conditions observed during the 2021–2025 monitoring period.

The visual observations support the results obtained from the climatic and mineralogical analyses, indicating that prolonged dry conditions and changes in atmospheric humidity have contributed to progressive land degradation in the study area. Representative photographs illustrating the main indicators of desertification are presented in Figures 1–6.

Figure 1. Proliferation of xerophytic drought-resistant vegetation on the terrace along the Kish River near the Qoxmuq bridge area (Captured on June 17, 2022, from coordinates: 41°13'54'' N, 47°11'14'' E). *Photo by M.A. Gahramanov.*

Figure 2. Seasonal phenological transformation and state of xerophytic vegetation on the same Kish River terrace near the Qoxmuq bridge area (Captured on November 3, 2022, from coordinates: 41°13'54'' N, 47°11'14'' E). *Photo by M.A. Gahramanov.*

Figure 3. Temporary surge in shrub vegetation biomass along the southern foothills of Mount Inja due to elevated springtime precipitation levels (Captured on June 17, 2022, from coordinates: 41º14'34"N, 47º05'56"E). *Photo by M.A. Gahramanov.*

Figure 4. Intensified denudation processes and a temporary substantial reduction in shrub vegetation biomass along the southern foothills of Mount Inja due to hyper-arid and elevated thermal conditions during the summer months (Captured on November 2, 2022, from coordinates: 41°14'34'' N, 47°05'56'' E). *Photo by M.A. Gahramanov.*

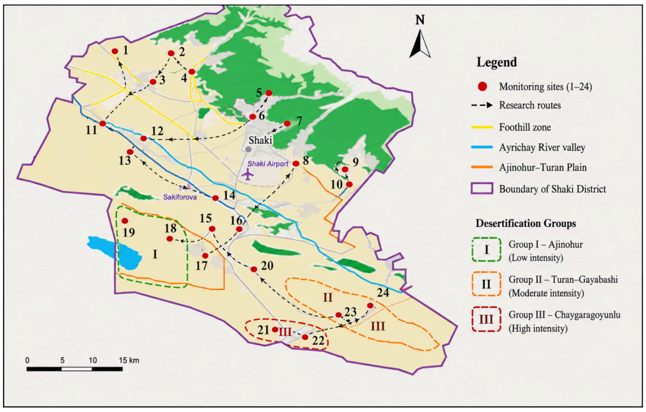
Figure 5. Landscape facies belonging to the *Rubus-Verbascum* (blackberry-mullein) plant association within the alluvial fan of the Kish River, Ayrichay valley (Captured on June 21, 2022, from coordinates: 41º12'24" N, 47º06'22" E). *Photo by M.A. Gahramanov.*

Figure 6. Arid-scorched and heavily weed-infested (thistle proliferation) cereal cultivation fields within the Ajinohur plateau, captured facing toward the Akharbakharsky ridge (Captured in July 2021, from coordinates: 41º00'25" N, 47º01'44" E). *Photo by H.L. Mustafabeyli.*

Map-Schematic 1 presents the spatial distribution of the field survey routes and the principal desertification monitoring sites within the Shaki District. The field investigations were conducted during the 2021–2025 monitoring period and covered the major landscape units, including the foothill zone, the Ayrichay riverbank, and the Ajinohur–Turan plain. These routes were selected to represent areas with different geomorphological, geological, and land-use characteristics.

Based on field observations, the investigated sites were classified into three desertification categories (Groups I–III) according to the observed intensity of land degradation. Group I represents areas with relatively low levels of degradation, Group II includes moderately degraded landscapes, and Group III comprises sites where desertification processes are most pronounced. This classification reflects differences in vegetation cover, soil erosion, surface degradation, and the influence of human activities across the study area.

The spatial distribution of the monitoring sites provides a framework for interpreting the meteorological, mineralogical, and field observations presented in the subsequent sections.



Map-Schematic 1. Schematic map of desertification monitoring zones within the Shaki district.

Research routes: 1 – Shin River (Abbas), **2** – Shin River (Bash Layski), **3** – Shin River (Ashaghi Goynuk), **4** – Shin River (Bash Goynuk), **5** – Gaynar River, **6** – Kish River, **7** – Gurjana River, **8** – Zayzit River, **9** – Gungut River, **10** – Oravan, **11** – Ayrichay River (Jumakand), **12** – Ayrichay River – Babaratma, **13** – Shorsu, **14** – Dashuz, **15** – Dashbulaq, **16** – Goybulaq; **Desertification Zone I: 17** – Boyuk Dahna, **18** – Kichik Dahna, **19** – Ajinohur, **20** – Dahnachay; **Desertification Zone III: 21** – Akharbakhar, **22** – Chaygaragoyunlu; **Desertification Zone II: 23** – Turan, **24** – Gayabashi.

Based on the synthesis and analytical evaluation of the conducted scientific research, the following critical regularities regarding desertification processes within the Shaki district have been established:

1. Classification of Driving Mechanisms: Desertification processes are systematically categorized into three main hierarchical groups governed by geographical, ecological, geological, biological, and anthropogenic forcing agents: a) the amplification of erosional-denudational processes on foothill slopes driven by escalating anthropogenic pressures; b) soil degradation and hyper-exploitation across the Ayrichay basin resulting from overgrazing; and c) severe soil erosion within the closed depressions of the Ajinohur plateau under acute irrigation water deficits.

2. Landscape Transformations and Xerofitisation: Empirical monitoring indicates that desertification processes are progressively intensifying across both the Alazan-Ayrichay plain and the Ajinohur plateau. This structural shift is characterized by accelerated gully formation on inclined plains and widespread xerofitisation within grain cultivation matrices, prominently marked by the proliferation of thistles (Cirsium) and camelthorn (Alhagi). Concurrently, a substantial decline in the abundance of key herbaceous species, such as St. John's wort (Hypericum), chamomile (Matricaria), thyme (Thymus), and other endemic forbs, has been documented within the alluvial lowland forest-meadow landscapes (Mustafabeyli, 2023).

3. Hydro-Technical Mitigation Measures: The construction of contour ditches (trenches) with approximate widths and depths of 1 meter within the deluvial apron zones formed along the southern slopes of the Greater Caucasus Mountains plays a vital role in ecological conservation. Directing rainfall and meltwater runoff into these ditches and specialized infiltration filters partially secures the local potable water supply while effectively decelerating local desertification trends.

In conclusion, these comprehensive field observations and analytical evaluations provide a rigorous framework for synthesizing the primary catalysts and spatial intensity profiles of desertification across the Shaki district.

CONCLUSION

Analytical evaluations spanning the 2021–2025 period indicate that the primary meteorological drivers accelerating desertification processes within the Shaki district are low relative humidity levels and frequent shifts in air mass circulation patterns. During the 2021–2023 baseline years, the mean annual relative humidity fluctuated within a critical 46–50% range, significantly fostering widespread soil desiccation. Although a marginal upward trend in relative humidity was documented during 2024–2025, it proved insufficient to counteract or halt the ongoing structural desertification. Notably, the high frequency of atmospheric variability during June, May, and October substantially intensified both localized soil erosion and macro-scale denudation processes.

One of the most critical meteorological catalysts driving the desertification process within the Shaki district is the prevailing macroclimatic aridity. This condition is fundamentally induced by severe thermal extremes during July and August 30-40 oC), coupled with a drop in diurnal relative humidity below the 30% threshold. Furthermore, during the winter cycle (January and February), the continuous decline of the diurnal relative humidity below 50% significantly exacerbates the overarching regional aridification.

Empirical field monitoring and visual assessments confirm that desertification dynamics across the Shaki district manifest with landscape-specific intensity. Persistent drought and microclimatic stress actively stimulate the expansion of xerophytic vegetation patches, drastically alter shrub biomass configurations, and trigger widespread weed infestation (thistle proliferation) within cereal cultivation matrices. Concurrently, the alternating sequence of pluvial and hyper-arid phases during the spring and summer months exerts a direct forcing impact on the acceleration of soil erosion and denudation rates. Consequently, these empirical observations serve as a direct visual validation of the combined impacts of relative humidity, temperature fluctuations, and atmospheric circulation dynamics on regional desertification trends.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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The impact of municipal management on socio-economic development in the Central Aran economic region

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ABSTRACT

This article examines the relationship between municipal management and socio-economic development in the Central Aran economic region of Azerbaijan. The study aims to identify the channels through which the financial, institutional and participatory capacities of local self-government may contribute to territorial development and to propose an indicator-based framework for assessment. Document analysis, comparative analysis, descriptive statistics and indicator-based evaluation are applied using publications of the State Statistical Committee of the Republic of Azerbaijan and international literature on local governance and regional development. The study covers Mingachevir city and the Aghdash, Goychay, Kurdamir, Ujar, Yevlakh and Zardab districts. Selected 2024 indicators show that 63.1% of households had a computer, while selected constraints related to food accessibility ranged from 1.3% to 2.4%; grain and leguminous crop production reached 318,817.5 tonnes. These indicators do not establish a causal municipal effect, but they demonstrate the multidimensional context in which local authorities operate. The analysis shows that municipal contribution should be assessed not only by financial resources, but also by institutional capacity, citizen participation, transparency, service accessibility, digitalization and coordination with other levels of government. The paper proposes a six-domain monitoring framework to support evidence-based local development planning in Central Aran.

INTRODUCTION

Contemporary approaches to regional development view the realization of territorial socio-economic potential not solely as an outcome of central government policy, but as the result of interaction among different levels of governance. Adapting decisions to local conditions, improving access to services, mobilizing local resources and expanding citizen participation are central elements of this approach. The OECD emphasizes the importance of regional and local indicators for evidence-based decision-making and promotes the use of comparable data on the economy, labour market, demography, transport, services and digital capacity (OECD, 2024a, 2024b).

The influence of local self-government on development outcomes is neither automatic nor linear. The decentralization literature shows that decision-making closer to citizens may provide informational advantages and strengthen accountability, yet outcomes depend on fiscal capacity, clarity of responsibilities, institutional quality and coordination (Faguet, 2014; Smoke, 2015). Municipal performance therefore cannot be adequately assessed only by the size of budgets or the number of completed activities, because such measures do not fully capture the role of local governance in development processes.

Systematic monitoring of social, economic, demographic and environmental indicators across economic regions is an important component of Azerbaijan's regional development policy. The statistical yearbooks Regions of Azerbaijan published by the State Statistical Committee provide city- and district-level data on population, income, the labour market, output, trade, construction, industry, transport, telecommunications and other fields (State Statistical Committee of the Republic of Azerbaijan, 2024, 2025a). These data provide a basis for tracking territorial disparities and the different dimensions of local development.

The Central Aran economic region comprises Mingachevir city and the districts of Aghdash, Goychay, Kurdamir, Ujar, Yevlakh and Zardab. The coexistence of urban and rural settlements together with industrial, agricultural, trade and service activities increases the need for territorially adapted governance instruments rather than a single uniform approach. In this context, systematically linking municipal governance with socio-economic indicators through an indicator-based framework has both scientific and practical relevance.

The main objective of this study is to identify the dimensions in which municipal governance intersects with socio-economic development in the Central Aran economic region, propose an indicator framework for assessing this relationship, and summarize priorities for local development planning using available statistical evidence. The study does not claim to measure causal effects; instead, it focuses on constructing an analytical structure that can later be tested using a broader municipality-level database.

LITERATURE REVIEW

One of the theoretical foundations linking local governance and regional development is the decentralization approach. Faguet (2014) argues that the advantages of local decision-making may arise from more accurate information about community needs and stronger accountability. However, whether these advantages translate into tangible outcomes depends on institutional design, fiscal resources and the capacity of local actors. Smoke (2015) likewise notes that decentralization is broader than the formal transfer of authority and requires the alignment of fiscal, administrative and political mechanisms.

The sustainability of municipal finance is a key condition for local development capacity. Local revenues, the composition of budget expenditure and investment capacity determine the scale at which a municipality can provide services and implement projects. At the same time, the volume of resources alone does not guarantee effective outcomes when financial autonomy is not complemented by accountability. Financial indicators should therefore be assessed together with measures of planning, transparency and project management.

Citizen participation and open information are additional dimensions of local governance quality. Public hearings, citizen applications, local initiatives and the clear presentation of budget information can help municipalities identify local needs more accurately. Digital tools can broaden this process through electronic applications, public information, online surveys and open-data mechanisms. Digital accessibility can therefore be considered both a socio-economic development indicator and an instrument that supports governance capacity.

In an internally diverse economic region such as Central Aran, the assessment of local governance must account for territorial characteristics. The needs of Mingachevir, with its more urban economic and service base, differ from those of districts in which agriculture plays a larger role. The OECD's multi-level governance approach also emphasizes that local and regional policy should reflect territorial specificity, coordination and comparable indicators (OECD, 2024a, 2024b). This perspective provides the conceptual basis for the multidimensional indicator framework applied in the present study.

MATERIALS AND METHODS

Study area

The study covers the Central Aran economic region, consisting of Mingachevir city and the districts of Aghdash, Goychay, Kurdamir, Ujar, Yevlakh and Zardab. The area is characterized by the Kura River system, the Mingachevir Reservoir, major transport corridors, agricultural land and the urban-industrial function of Mingachevir. Figure 1 presents the administrative structure of the study area and its principal hydrographic features.

Figure 1. Study area and administrative structure of the Central Aran economic region.

Source: Author's elaboration in QGIS based on administrative boundary and hydrographic spatial data.

Data sources and analytical approach

The study combines document analysis, comparative analysis, descriptive statistics and indicator-based assessment. The principal data sources are the Regions of Azerbaijan statistical yearbooks published by the State Statistical Committee of the Republic of Azerbaijan, economic-region indicators for 2024, and the publication Digital Development in Azerbaijan, 2025. These sources enable the regional socio-economic context to be described and the selected indicators to be systematized.

The analytical variables are grouped into six dimensions: financial capacity; institutional capacity; citizen participation and transparency; indicators related to economic development; social well-being and access to services; and infrastructure and digitalization. This grouping helps distinguish factors under more direct municipal influence from the broader socio-economic environment in which municipalities operate.

The main methodological limitation is the absence of a long-term, harmonized and openly available municipality-level panel covering financial and activity data across the entire region. The results are therefore not interpreted as correlation coefficients or causal estimates. Instead, the indicators are used to identify plausible channels through which municipal governance may matter and to define measurable variables for future empirical research.

Table 1. Indicators for assessing municipal governance and socio-economic development

Dimension	Key indicators	Purpose of assessment
Financial capacity	Local revenues; budget revenues and expenditures; investment capacity	Financial sustainability
Institutional capacity	Staffing; planning; accountability; transparency	Governance capacity
Participation	Public hearings; citizen applications; local initiatives	Citizen participation
Economic development	Employment; entrepreneurship; output; investment	Local economic dynamics
Social development	Income; access to services; living conditions	Changes in well-being
Infrastructure and digitalization	Roads; utilities; internet; digital capacity	Accessibility and service quality

Source: Compiled by the author based on OECD approaches and the analytical framework of the study.

RESULTS AND DISCUSSION

Socio-economic context of Central Aran

The analysis indicates that the socio-economic development of Central Aran cannot be adequately characterized by a single indicator. Levels of urbanization, the role of agriculture, labour-market structure, access to services and digital capacity vary across the region. Municipal governance should therefore be assessed through a data system that captures both the overall regional picture and differences at district and municipal levels.

Selected indicators for 2024 illustrate the need for this multidimensional approach. In Central Aran, 63.1% of households had a computer. Selected indicators of constraints on economic access to food ranged from 1.3% to 2.4%, while production of grain and leguminous crops reached 318,817.5 tonnes (State Statistical Committee of the Republic of Azerbaijan, 2025b). These indicators cover different domains and demonstrate the importance of monitoring the digital, social and productive dimensions of local development in parallel.

Table 2. Selected socio-economic indicators for the Central Aran economic region, 2024

Indicator	Year	Central Aran
Share of households with a computer	2024	63.1%
Households worried about not having enough food	2024	1.4%
Households unable to consume healthy and nutritious food	2024	1.3%
Households not living near outlets selling a sufficient variety of essential food products	2024	2.4%
Production of grain and leguminous crops	2024	318,817.5 tonnes

Source: State Statistical Committee of the Republic of Azerbaijan, 2024 statistical materials and Digital Development in Azerbaijan, 2025.

Potential channels of municipal governance influence

One of the principal findings is that the relationship between municipal governance and socio-economic development is better understood through several interacting channels rather than as a single direct mechanism. The first channel is the mobilization of local financial resources and their allocation according to territorial needs. The second is the more accurate identification of local problems and the preparation of decisions through interaction with citizens. The third is coordination between municipalities and state institutions, businesses, civil society and other local actors.

A fourth channel is the digitalization of governance and service processes. Although the 63.1% share of households with a computer indicates a foundation for the use of digital services, this figure does not imply digital equality. Electronic application and information channels should complement rather than fully replace conventional service delivery, while alternative access options should remain available for groups with limited digital connectivity.

Figure 2 summarizes these channels in an indicator-based analytical framework. Financial capacity, institutional capacity, participation and transparency, and coordination and digitalization are presented as the principal dimensions shaping local governance capacity. Their outcomes can be monitored through indicators of economic dynamics, social well-being, infrastructure and service accessibility.

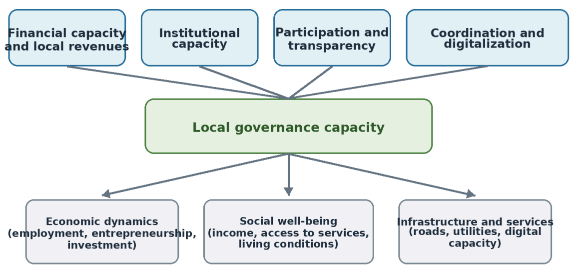

Figure 2. Indicator-based analytical framework linking municipal governance and socio-economic development.
Source: Prepared by the author.

Territorial differences and local development priorities

Territorial differences are particularly important when assessing municipal governance in Central Aran. In an urban setting such as Mingachevir, municipal services, public space, digital services, small business support and urban infrastructure may have greater priority. In districts with more dispersed rural settlements, road accessibility, agriculture-related local infrastructure, water and utility services, market access and intermunicipal cooperation may be more important. These differences require a common indicator panel to be complemented by context-specific sub-indicators.

The first practical recommendation is to establish a minimum indicator panel for municipalities. Annual data should be collected and disclosed using a consistent methodology across financial capacity, service delivery, participation, economic activity, social well-being and digitalization. This would enable more transparent comparisons of changes over time and differences among municipalities.

The second recommendation is to link local development plans to measurable targets. Reports should monitor not only the number of activities undertaken or works completed, but also outcome indicators such as improvements in service access, response time to citizen applications, the collection rate of local revenues, the population served by small infrastructure projects and the use of digital services.

A third priority is to strengthen transparency and citizen participation. Presenting budget priorities, projects, revenue sources and expenditures in an accessible format may increase public engagement in decision-making and improve the quality of information on local needs. A fourth priority is to expand intermunicipal cooperation. Joint action can increase efficiency in areas such as waste management, service infrastructure and regional projects that exceed the financial or technical capacity of a single municipality.

A fifth priority is to expand digital governance tools. Electronic applications, open data, online surveys, visualization of budget information and digital tracking of project implementation can strengthen both service accessibility and accountability. However, digital tools should be treated as mechanisms that support, rather than substitute for, the quality of institutional processes.

Study limitations

Because this study relies mainly on open-source regional statistics and document analysis, it does not estimate statistical causal relationships between individual components of municipal governance and socio-economic outcomes. The limited availability of harmonized annual municipality-level data on finance, services and participation prevents comparative econometric analysis. The findings should therefore be interpreted as an analytical framework and monitoring proposal. Future research could combine multi-year panel data, correlation and regression models, and surveys or interviews with municipal officials and residents to assess the strength of these relationships more precisely.

CONCLUSIONS

The study shows that assessing the relationship between municipal governance and socio-economic development in the Central Aran economic region requires a multidimensional approach. Rather than evaluating municipalities only through financial indicators or individual completed activities, it is more appropriate to consider institutional capacity, citizen participation, transparency, local resource mobilization, access to services, economic activity and digital capacity together.

The scientific and practical contribution of the study is the proposal of an indicator system that links municipal governance and socio-economic development measures within a unified assessment framework for Central Aran. The available 2024 indicators reflect different digital, social and productive characteristics of the region, but they should not be interpreted as evidence of a causal municipal effect.

Overall, more effective local development policy in Central Aran requires stronger evidence-based planning, standardized indicators, measurable outcome targets, citizen participation, intermunicipal cooperation and multi-level coordination. The future development of municipality-level panel data would make it possible to test the proposed framework using statistical methods.

AUTHOR CONTRIBUTIONS

Conceptualization, N.A.; methodology, N.A.; investigation, N.A.; formal analysis, 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

The data used in this study are derived from publicly accessible statistical sources cited in the manuscript. The selected indicators are reported in the tables, and the analytical framework is presented in Figure 2.

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