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COMPARATIVE EVALUATION OF INNOVATIVE TRANSPORT SYSTEMS FOR ENVIRONMENTAL SUSTAINABILITY AND ENERGY EFFICIENCY

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Abstract- The transport sector is one of the major contributors to environmental degradation, air pollution, and greenhouse gas emissions, particularly in rapidly urbanizing and energy-dependent economies such as Azerbaijan. Increased motorization, reliance on fossil fuels, traffic congestion, and inefficient transport management have intensified ecological challenges, especially in large metropolitan areas. In response to these issues, Azerbaijan has initiated a range of innovative transport projects aimed at reducing environmental impacts, improving energy efficiency, and supporting sustainable development objectives. This paper presents a comparative analysis of key innovative transport initiatives implemented in Azerbaijan, including electric public transport systems, intelligent transport systems (ITS), railway electrification, and green mobility projects such as cycling infrastructure and micromobility solutions. The evaluation framework is based on environmental, economic, and operational criteria, including CO_2 emission reduction potential, energy efficiency gains, implementation costs, and long-term sustainability. The results of the comparative analysis indicate that railway electrification and electric public transport provide the most significant reductions in greenhouse gas emissions and energy consumption, while ITS and green mobility projects offer cost-effective and rapidly deployable solutions with notable indirect environmental benefits. The findings highlight that integrated deployment of multiple innovative transport solutions yields greater environmental and operational efficiency than isolated project implementation.

The study concludes that innovative transport projects play a crucial role in mitigating Azerbaijan's environmental challenges and advancing national sustainability and energy policy goals. The outcomes of this research provide practical insights for policymakers, transport planners, and stakeholders seeking to design environmentally responsible and economically viable transport systems aligned with international sustainability standards. The findings contribute directly to the achievement of SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), and SDG 9 (Industry, Innovation and Infrastructure) by demonstrating how integrated innovative transport solutions reduce environmental impacts, enhance energy efficiency, and support sustainable urban development in Azerbaijan.

Keywords: Electric Public Transport, Railway Electrification, Intelligent Transport Systems (ITS), Green Mobility Solutions, Sustainable Urban Transport, CO_2 Emission Reduction, Energy Efficiency in Transport, Micromobility Infrastructure, Integrated Transport Policy, Sustainable Development Goals (SDGs).

1. INTRODUCTION

The transport sector plays a crucial role in economic development, regional connectivity, and social integration; however, it remains one of the major sources of environmental pollution and energy consumption. Road transport emissions, fossil fuel dependency, and traffic congestion contribute significantly to greenhouse gas emissions, air quality deterioration, and climate-related risks, particularly in rapidly urbanizing and transition economies. In Azerbaijan, the transport sector holds strategic importance due to its role as a regional transport and logistics hub connecting Europe and Asia. At the same time, increasing motorization, concentration of economic activity in urban areas, and reliance on petroleum-based fuels have intensified environmental

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pressures. Urban centers, especially Baku, face persistent challenges related to air pollution, congestion, and inefficient energy use, highlighting the need for sustainable transport solutions [1].

In response, Azerbaijan has initiated a range of innovative transport projects aligned with national sustainability strategies and international climate commitments. These initiatives emphasize electrification, digitalization, and the development of environmentally friendly mobility alternatives. Key areas include electric public transport systems, Intelligent Transport Systems (ITS), railway electrification, and green mobility solutions. These innovations aim to reduce emissions, improve energy efficiency, and enhance overall transport system performance without limiting mobility demand. Despite the growing implementation of such projects, a systematic comparative evaluation of their environmental and operational effectiveness remains limited. Existing studies often focus on individual technologies, providing insufficient insight into their relative performance and interaction within a broader transport system. This creates a gap in evidence-based decision-making, particularly in prioritizing investments and policy measures [2].

The objective of this study is to conduct a comparative analysis of major innovative transport projects in Azerbaijan using a multi-criteria evaluation framework. The research assesses electric public transport, ITS, railway electrification, and green mobility initiatives based on environmental, economic, and operational indicators. In addition, the study examines the sensitivity of results to different evaluation priorities and explores the synergistic effects of integrated transport strategies. The findings contribute to the understanding of how coordinated transport innovations can support sustainable development and provide practical insights for policymakers and transport planners in designing efficient and environmentally responsible transport systems [3].

2. ENVIRONMENTAL CHALLENGES OF THE TRANSPORT SECTOR IN AZERBAIJAN

The transport sector in Azerbaijan represents one of the most significant sources of environmental pressure, primarily due to its strong dependence on fossil fuels, rapid growth in motorization, and increasing urban traffic demand. While the sector plays a vital role in supporting economic activity and regional connectivity, its environmental footprint has expanded considerably over the past decades, creating complex sustainability challenges that require targeted policy and technological responses [4].

One of the most critical environmental challenges is air pollution caused by road transport emissions. The dominance of internal combustion engine vehicles results in high levels of carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and particulate matter (PM). These pollutants are particularly concentrated in large urban areas, where traffic congestion and frequent stop-and-go driving patterns significantly increase emission intensity. In cities such as Baku, transport-related air pollution has become a major concern due to its adverse impacts on public health, urban livability, and environmental quality.

Another major challenge is the high level of energy consumption and low energy efficiency within the transport sector. Road transport accounts for the largest share of final energy use in the sector, with petroleum products remaining the dominant energy source. This reliance on fossil fuels not only increases greenhouse gas emissions but also exposes the transport system to fuel price volatility and long-term energy security risks. Compared to rail and electric transport modes, road-based transport demonstrates lower energy efficiency per passenger-kilometer and ton-kilometer, intensifying the environmental burden.

Traffic congestion further exacerbates environmental problems by increasing fuel consumption, emissions, and travel time losses. Inefficient traffic management, limited use of adaptive control systems, and the concentration of travel demand during peak hours contribute to excessive idling and reduced average vehicle speeds. As a result, even modern vehicles with improved emission standards often operate under suboptimal conditions, diminishing their potential environmental benefits [5].

In addition to air pollution and energy inefficiency, the transport sector contributes to noise pollution and land-use pressure, particularly in densely populated urban areas. High traffic volumes generate continuous noise levels that negatively affect human health and quality of life. At the same time, the expansion of road infrastructure increases land consumption, disrupts urban ecosystems, and reduces green spaces, creating long-term environmental and social costs.

The modal imbalance in Azerbaijan's transport system represents another structural challenge. The predominance of private car use over public and non-motorized transport limits the effectiveness of emission reduction strategies. Although rail transport offers a more environmentally efficient alternative for both passenger and freight movement, its potential remains underutilized in certain corridors due to infrastructure limitations and service integration issues [6].

Overall, the environmental challenges of Azerbaijan's transport sector are multifaceted and interconnected, encompassing emissions, energy use, congestion, noise, and spatial impacts. Addressing these issues requires not only regulatory measures but also the adoption of innovative transport solutions that promote electrification, digitalization, modal shift, and system optimization. Understanding the nature and scale of these challenges provides a critical foundation for evaluating the role of innovative transport projects in mitigating environmental impacts, which is the focus of the subsequent sections of this study [7].

3. INNOVATIVE TRANSPORT PROJECTS IN AZERBAIJAN

In recent years, Azerbaijan has increasingly prioritized the development and implementation of innovative transport projects as a core component of its

environmental and sustainable development strategy. These projects aim to reduce the negative environmental impacts of transport activities while simultaneously improving system efficiency, service quality, and energy performance. The country's approach focuses on technological modernization, digitalization, electrification, and the promotion of environmentally friendly mobility alternatives.

3.1. Electric Public Transport Systems

The expansion of electric public transport represents one of the most visible and impactful innovations in Azerbaijan's transport sector. This includes the modernization of the Baku Metro system, the introduction of electric buses, and the gradual replacement of conventional diesel-powered public transport vehicles. Electric transport systems offer zero direct exhaust emissions, significantly reduced noise levels, and higher energy efficiency compared to internal combustion engine vehicles.

In urban environments, electric buses and metro services play a crucial role in reducing CO_2 emissions and improving air quality, particularly along high-demand corridors. Although the initial investment costs associated with vehicle procurement and charging infrastructure are relatively high, long-term operational savings and environmental benefits make electric public transport a strategically important solution. Moreover, when combined with cleaner electricity generation, the overall carbon footprint of electric transport is further reduced [8].

3.2. Intelligent Transport Systems (ITS)

Intelligent Transport Systems (ITS) constitute another key category of innovation, focusing on optimizing traffic management rather than expanding physical infrastructure. In Azerbaijan, ITS applications include adaptive traffic signal control, traffic monitoring and surveillance systems, electronic tolling, and smart public transport management platforms.

By improving traffic flow and reducing congestion, ITS indirectly contributes to emission reductions and fuel savings. Shorter travel times, fewer stop-and-go cycles, and better incident management lead to lower energy consumption per trip. Compared to large-scale infrastructure projects, ITS solutions are relatively cost-effective and can be implemented rapidly, making them particularly suitable for densely populated urban areas. Their effectiveness is further enhanced when integrated with public transport prioritization and real-time information systems.

3.3. Railway Electrification and Modernization

Railway electrification is among the most environmentally effective transport innovations implemented in Azerbaijan, particularly for long-distance passenger and freight transport. Electrified railways offer significantly lower emissions per passenger-kilometer and ton-kilometer compared to road transport, as well as higher energy efficiency and operational reliability. Modernization projects targeting key railway corridors aim to shift transport demand from road to rail, thereby reducing congestion and emissions across the entire transport system. While railway electrification requires substantial capital investment and long implementation periods, its long-term environmental and economic benefits are considerable. The integration of modern signaling systems, energy-efficient rolling stock, and digital traffic management further enhances the sustainability performance of rail transport as illustrated in Figure 1.

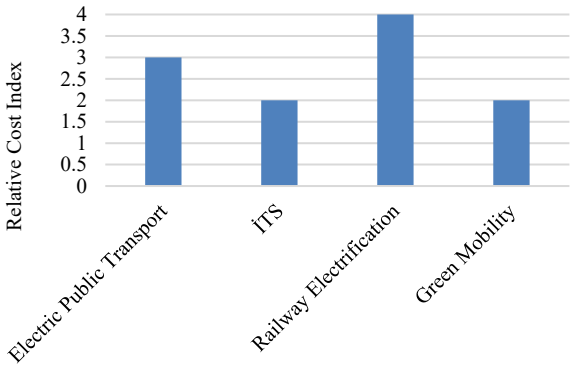

Figure 1. Relative implementation cost of innovative transport projects

Figure 1 compares the relative implementation costs of innovative transport projects. While railway electrification requires higher initial investment, ITS and green mobility projects are more cost-effective and rapidly deployable.

3.4. Green Mobility and Non-Motorized Transport Initiatives

Green mobility initiatives focus on promoting environmentally friendly travel modes for short-distance and urban trips. In Azerbaijan, these projects include the development of cycling infrastructure, pedestrian-friendly urban spaces, and the introduction of micromobility solutions such as shared bicycles and electric scooters. These initiatives provide zero-emission transport alternatives, reduce traffic congestion, and contribute to improved public health and urban livability. Green mobility projects are characterized by low implementation costs, high social acceptance, and rapid deployment potential. However, their effectiveness depends on urban planning integration, safety measures, and public awareness.

3.5. Integrated Impact of Innovative Transport Projects

The overall environmental effectiveness of innovative transport projects in Azerbaijan is maximized when these solutions are implemented in an integrated manner. For instance, the combination of electric public transport and ITS enhances both emission reduction and operational efficiency, while green mobility initiatives complement public transport by addressing first- and last-mile connectivity. Such systemic integration supports a transition toward a low-carbon, energy-efficient, and resilient transport system [9]. The comparative characteristics of innovative transport projects are summarized in Table 1.

Table 1. Comparative characteristics of innovative transport projects in Azerbaijan

Project Type	Key Technologies	Environmental Impact	Energy Efficiency	Implementation Cost	Deployment Speed
Electric Public Transport	Electric buses, metro electrification, charging infrastructure	High CO_2 and air pollutant reduction	High	Medium-High	Medium
Intelligent Transport Systems (ITS)	Adaptive signals, traffic monitoring, smart control	Medium (indirect emission reduction)	Medium	Low-Medium	High
Railway Electrification	Electric traction, modern rolling stock, digital signaling	Very High	Very High	High	Low
Green Mobility	Cycling lanes, pedestrian zones, micromobility	High (zero direct emissions)	Very High	Low	Very High

4. COMPARATIVE ANALYSIS OF INNOVATIVE TRANSPORT PROJECTS

A comparative analysis of innovative transport projects is essential to evaluate their relative effectiveness in addressing environmental challenges and improving transport system performance. In this study, four major categories of transport innovation implemented in Azerbaijan, electric public transport, intelligent transport systems (ITS), railway electrification, and green mobility initiatives, are assessed using a multi-criteria analytical framework. The evaluation focuses on environmental impact, energy efficiency, economic feasibility, implementation complexity, and long-term sustainability.

From an environmental perspective, railway electrification demonstrates the highest potential for reducing greenhouse gas emissions and air pollutants. Due to its high energy efficiency and ability to accommodate large passenger and freight volumes, electrified rail transport offers the lowest emission levels per passenger-kilometer and ton-kilometer. Electric public transport systems also provide substantial emission reductions, particularly in urban environments, by eliminating direct exhaust emissions and reducing noise pollution. Green mobility initiatives, although limited in scale, deliver zero-emission solutions for short-distance travel and contribute positively to urban air quality as illustrated in Figure 2.

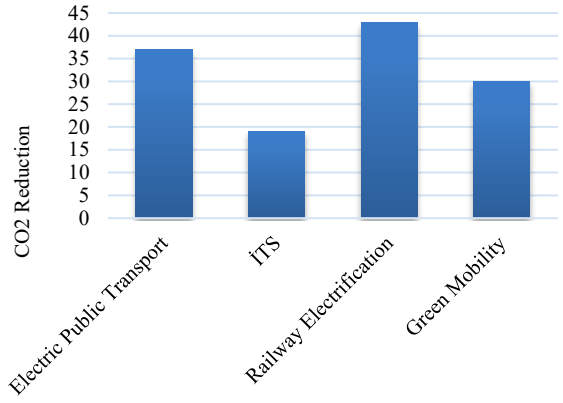

Figure 2. Comparative CO_2 emission reduction by innovative transport projects

Figure 2 illustrates the comparative CO_2 emission reduction potential of innovative transport projects in Azerbaijan. Railway electrification demonstrates the highest emission reduction effect, followed by electric public transport and green mobility initiatives. In contrast, ITS solutions produce environmental benefits primarily through indirect mechanisms. By optimizing traffic flow, reducing congestion, and minimizing idling time, ITS contributes to lower fuel consumption and emission levels. While the magnitude of emission reduction achieved through ITS is generally lower than that of electrification-based projects, its cost-effectiveness and rapid deployment potential make it a valuable complementary solution [10].

In terms of energy efficiency, green mobility and railway electrification rank highest, as they either eliminate fuel consumption entirely or significantly reduce energy use per transport unit. Electric public transport occupies an intermediate position, offering high efficiency but remaining dependent on the energy mix used for electricity generation. ITS projects improve energy efficiency indirectly by optimizing operational conditions rather than altering vehicle technology. As illustrated in Figure 3.

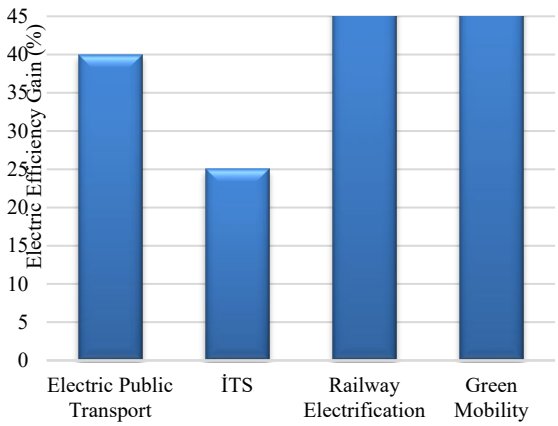

Figure 3. Energy efficiency improvements across transport innovations

As shown in Figure3, green mobility and railway electrification provide the highest energy efficiency gains, highlighting their strategic importance in achieving sustainable transport objectives. The economic dimension of the analysis reveals notable differences among the project types. ITS and green mobility initiatives require relatively low capital investment and deliver quick returns through reduced congestion, fuel savings, and improved service quality. Electric public transport and railway electrification involve higher upfront costs associated with infrastructure development and vehicle procurement; however, these investments generate substantial long-term economic and environmental benefits, particularly when evaluated over the full lifecycle of the systems.

Regarding implementation complexity and scalability, green mobility and ITS projects are the easiest to deploy and scale across urban areas. Railway electrification, while offering the greatest environmental benefits, requires long planning horizons, complex coordination, and substantial financial resources. Electric public transport systems occupy a middle position, with moderate implementation complexity and strong scalability potential in densely populated corridors [11].

Overall, the comparative analysis highlights that no single innovative transport project can independently resolve environmental challenges. Instead, the most effective strategy involves an integrated approach that combines electrification, digitalization, and modal diversification. The synergy among different innovative solutions enhances their collective impact, supporting Azerbaijan's transition toward a sustainable, energy-efficient, and environmentally responsible transport system. Figure 4 illustrates the trend of CO_2 emission reduction achieved through different innovative transport projects in Azerbaijan over time, highlighting the increasing environmental benefits of electrification-based solutions.

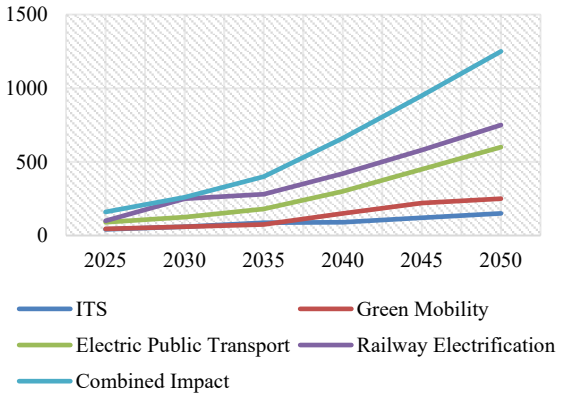

Figure 4. Trend of CO_2 emission reduction under innovative transport projects

4.1. Sensitivity and Analytical Interpretation of Environmental Impact Index

The Environmental Impact Index (EII) serves as a composite indicator integrating multiple performance criteria, including emission reduction potential, energy efficiency, implementation cost, and operational effectiveness. While this index provides a structured basis for comparison, its results are inherently dependent on the selected weighting coefficients assigned to each criterion. To evaluate the robustness of the findings, a sensitivity analysis was conducted by varying the weight distribution across environmental and economic dimensions. The baseline scenario assigns higher importance to environmental criteria (e.g., emission reduction and energy efficiency), reflecting sustainability-oriented policy priorities. However, alternative scenarios were considered in which economic factors, such as implementation cost and deployment speed, were given greater weight.

The results demonstrate that railway electrification consistently ranks as the most effective solution under environmentally focused weighting schemes, due to its superior emission reduction capacity and energy efficiency. However, when economic criteria are prioritized, Intelligent Transport Systems (ITS) and green mobility initiatives gain relative importance due to their lower implementation costs and faster deployment. This shift in ranking highlights the sensitivity of composite indices to policy priorities and decision-making contexts. It suggests that the "optimal" transport solution is not absolute but depends on strategic objectives, such as short-term cost minimization versus long-term environmental sustainability.

Furthermore, the analysis reveals that electric public transport maintains a relatively stable position across different weighting scenarios, indicating its balanced performance across environmental and economic dimensions. These findings emphasize the importance of transparent weighting selection and support the use of multi-scenario evaluation frameworks in transport planning. Policymakers should therefore interpret composite indices not as fixed rankings but as flexible decision-support tools that reflect varying strategic priorities [12].

5. DISCUSSION

The results of the comparative analysis reveal that the effectiveness of innovative transport projects is not uniform but strongly dependent on their functional role within the transport system and the policy context in which they are implemented. The observed differences in environmental performance, energy efficiency, and economic feasibility can be explained by the structural characteristics of each transport innovation. Electrification-based solutions, particularly railway electrification and electric public transport, demonstrate the highest environmental effectiveness due to their direct impact on emission reduction and energy consumption. Their advantage stems from the ability to replace fossil fuel-based transport processes with more energy-efficient electric systems. However, this advantage is conditional on the energy mix used for electricity generation. In systems with a higher share of renewable energy, the environmental benefits of electrification increase significantly, whereas dependence on fossil-based electricity reduces its overall effectiveness [13].

In contrast, Intelligent Transport Systems (ITS) improve transport system performance through operational optimization rather than technological substitution. Their impact is primarily indirect, achieved by reducing congestion, minimizing idle time, and improving traffic flow. This explains why ITS demonstrates lower emission reduction potential compared to electrification but higher cost-effectiveness and faster implementation. From a systems perspective, ITS acts as an efficiency-enhancing layer that maximizes the performance of existing infrastructure.

Green mobility solutions exhibit a different type of impact, focusing on behavioral and modal shifts rather than system-wide technological change. Their effectiveness lies in reducing short-distance vehicle trips and promoting zero-emission alternatives. Although their aggregate contribution to national emission reduction is limited, their role in shaping sustainable mobility patterns and reducing urban externalities is significant [14]. A key analytical insight of this study is the sensitivity of evaluation results to the weighting structure of the applied criteria. The Environmental Impact Index (EII), as a composite indicator, reflects underlying policy priorities. When environmental criteria are prioritized, electrification solutions dominate the ranking; however, when economic efficiency and implementation speed are emphasized, ITS and green mobility solutions become comparatively more advantageous. This demonstrates that there is no universally optimal solution, and transport policy decisions must be aligned with strategic objectives.

A more detailed examination of these interaction effects is presented in the following subsection. The results indicate that integrated implementation generates synergistic benefits that exceed the sum of individual impacts. Electrification reduces emissions intensity, ITS enhances operational efficiency, and green mobility supports modal shift. Together, these mechanisms create a more balanced and resilient transport system. The presence of such complementarities explains why integrated scenarios consistently outperform isolated interventions in both environmental and operational terms. Overall, the analysis suggests that the transition toward sustainable transport systems should not be based on single-technology solutions but on coordinated, multi-dimensional strategies. The effectiveness of innovative transport projects depends on their integration within a broader system that simultaneously addresses technological, operational, and behavioral dimensions.

5.1. Mechanisms of Synergy in Integrated Transport Systems

The superior performance of integrated transport strategies can be explained by the interaction effects between different technological and operational components. Rather than functioning independently, innovative transport solutions reinforce each other through multiple mechanisms. For instance, the combination of electric public transport and Intelligent Transport Systems (ITS) enhances both environmental and operational efficiency. While electrification reduces direct emissions, ITS optimizes traffic flow and prioritizes public transport, increasing system utilization and reducing energy waste.

Similarly, green mobility solutions improve first- and last-mile connectivity, increasing the attractiveness and accessibility of public transport systems. This modal integration encourages a shift away from private car use, amplifying the overall emission reduction impact.

Railway electrification also benefits from integration with logistics optimization systems and digital traffic management, which improve capacity utilization and reduce idle energy consumption. These interaction effects demonstrate that the environmental benefits of integrated transport systems are not merely additive but multiplicative. The combined implementation of multiple innovations leads to systemic efficiency gains that exceed impact of individual solutions applied in isolation [15].

6. CONCLUSION

This study demonstrates that innovative transport projects play a critical role in addressing environmental challenges in Azerbaijan. Among the evaluated solutions, railway electrification and electric public transport provide the highest long-term environmental benefits, while ITS and green mobility offer flexible and cost-effective short-term improvements. Importantly, the findings reveal that the effectiveness of transport innovations is highly dependent on policy priorities and evaluation criteria. Sensitivity analysis shows that different weighting assumptions can significantly influence the relative ranking of solutions, emphasizing the need for transparent and context-specific decision-making.

The results also confirm that integrated transport strategies generate synergistic effects, where the combined implementation of multiple innovations produces greater environmental and operational benefits than isolated approaches. Overall, the study highlights that sustainable transport development requires not only technological innovation but also systemic integration, long-term planning, and alignment with energy and environmental policies.

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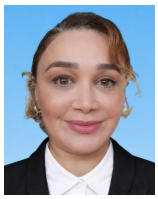

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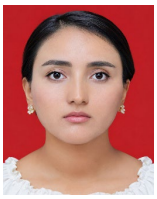
Research Interests: Active and Nanocomposite Materials
Scientific Publications: 30 Papers



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Research Interests: Ecological Engineering, Environment
Scientific Publications: 4 Papers