Managing Urban Wastewater Systems with an Economic and Environmental Approach

Normat Durdiev[1,*], Maksud Fayzullaev[2], Barno Kurbonova[3], Sabina Nasirova[4], Tulkin Kuyliyev[5], and Kassem Jumma[6]

[1]Department of Hydro-Amelioration Systems, Tashkent Institute of Irrigation and Agricultural Mechanization Engineers Institute, National Research University, 100000 Tashkent, Uzbekistan
[2]Department of Geography, Shahrisabz State Pedagogical Institute, Shakhrisabz street, 181301 Shakhrisabz city, Uzbekistan
[3]Department of Architecture, Samarkand State University of Architecture and Civil Engineering, 140100, Samarkand, Uzbekistan
[4]Department Clinic Pharmacology, Bukhara State Medical Institute named after Abu Ali Ibn Sino, Bukhara, Uzbekistan
[5]Department of Social and Humanities, Tashkent State Agrarian University, Tashkent, Uzbekistan
[6]Department of Computers Techniques Engineering, College of Technical Engineering, The Islamic University, Najaf, Iraq
Email: haliru.aa@gmail.com (N.D.); retnosuset@gmail.com (M.F.); barno.sayfabd@gmail.com (B.K.); sherzoodabdu@gmail.com (S.N.); mmjam.counsel@gmail.com (T.K.); kassem.jumma1892@gmail.com (K.J.)
*Corresponding author

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***Abstract*—The issue of sustainable urban wastewater management with an integrated economic and environmental approach is highly relevant, especially to developing countries such as Uzbekistan, which are faced with water resource scarcity and the effects of climate change. The objective of this research was to formulate and evaluate hybrid models of urban wastewater management in a bid to achieve a balance between economic and environmental goals. This study was conducted using a combination of methods, including cost-benefit analysis, life cycle assessment, field sampling, and software modeling, focusing on three major cities in Uzbekistan: Tashkent, Samarkand, and Bukhara. The results demonstrated that hybrid and natural systems, compared to conventional systems, can reduce life cycle costs by 30 to 50% and significantly improve key wastewater quality parameters by 40 to 60% (e.g., achieving BOD concentrations below 10 mg/L and total nitrogen below 8 mg/L). These systems also improved resource efficiency significantly by reducing energy consumption by 55 to 80% and increasing water recovery rates to more than 80%. Additionally, the combined sustainability index for hybrid systems showed a mark of 8.4 out of 10, which is significantly better than conventional systems. These findings confirm that the application of hybrid natural and engineered technologies is not only economically viable but also facilitates environmental reliability and resilience to climate change. It is therefore recommended that hybrid systems be integrated into national policy and urban planning in Uzbekistan to maximize progress toward the Sustainable Development Goals.**

***Keywords*—urban wastewater management, hybrid systems, cost-benefit analysis, Uzbekistan, environmental indicators**

I. Introduction

Urban wastewater management is currently among the most daunting challenges facing societies in today's world. With the expansion of cities and the spread of urbanization, there has been a tremendous expansion of wastewater volume, placing unparalleled pressure on natural resources alongside the existing infrastructure [1]. In countries like Uzbekistan, affected by water shortage and climate change, it is not just a technical problem, but a complex crisis affecting public health, the economy, and the environment [2]. So, it seems that one would need to look for new approaches to governing such systems in a manner that would provide a sustainable balance between human needs and nature preservation. Environmentally, untreated urban wastewater may flow into rivers, lakes, and land, transferring harmful pollutants into these environments. These harmful pollutants result in poor water quality, loss of biodiversity, and even transmission of diseases through water. In the case of Uzbekistan, where the majority of its water supplies are based on transboundary rivers, inefficient wastewater management can have a permanent impact on vulnerable ecosystems such as the Aral Sea. This is a strong pointer to an imperative need for technologies that not only reduce pollution but also serve to restore the environment [3].

The financial aspect of wastewater treatment cannot be ignored either. The expense of building and running treatment plants and the squandering of resources are costly on the coffers of governments and municipalities [4]. At the same time, smart investment in this industry can generate jobs, generate power from wastewater, and even generate income from water recycling. For Uzbekistan, with its industrial and agricultural economy, economic efficiency of wastewater plants can make imports less dependent on water and increase productivity, necessitating the quest for hybrid economic-environmental models. Synthesizing economic and environmental planning in urban wastewater management is to blame for encouraging sustainable development [5]. Such planning allows cost-benefit analysis to be applied to decision-making, while the environment is valued in an appropriate manner. Without synthesizing these dimensions, technical solutions would be limited to being short-term and do not address long-term concerns such as climate change. Therefore, research that compares these two dimensions can provide useful models for policymakers [6].

In Uzbekistan, despite the recent achievements in the construction of urban infrastructure, there are a lot of problems with wastewater management. Many cities are burdened with ineffective and outdated systems leading to water loss and pollution of resources [4]. This is not only unhealthy for residents' health, but also harms the local economy because agriculture and tourism depend on the state of the environment. Therefore, the focus on innovative solutions can eliminate these problems and transform Uzbekistan into an example for the region. Importance of this research lies in the fact that it will help national policy makers distribute limited resources effectively [7, 8]. With

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learning from successful foreign models and adapting them to the existing local environment, recommendations for cost-effective as well as environmentally friendly solutions are possible. Not only will pollution be avoided, but also people will be brought closer to the United Nations Sustainable Development Goals and the quality of life will improve [9].

Finally, it is necessary to conduct this study because wastewater management in cities is not a voluntary option anymore, but a requirement for the survival of people. With the increasing pressure on natural resources in Uzbekistan, this study can become a bridge between science and practice that will lead to the development of sustainable systems for future generations.

II. Literature Review

In recent literature, management of urban wastewater systems has been recognized as one of the cornerstones of sustainable urban development [10]. Different studies confirm that with the rapid growth of urbanization, the volume of wastewater generated has risen, hence the need for integrated approaches in order to prevent water crises [11]. The major issue is that traditional systems are not responsive any longer and that there is an urgency to move towards models that are operationally effective as well as locally responsive. This literature points out that wastewater management is not just a technical issue, but part of the urban water cycle that affects health, economy and ecology [12]. From the environmental perspective, studies indicate that wastewater from cities, if not treated, contaminates surface and groundwaters. In the majority of cases, chemical and biological pollutants lead to loss of biodiversity and disturbance in the ecosystem [13]. The literature adds that in arid and semi-arid regions such as regions in Central Asia, pollutions lead to long-term impacts such as salinization of the ground and loss of water resources. Environmental remedies suggest using natural technologies such as artificial wetlands or plant filters to reduce pollution and restore the environment [14, 15].

The economic aspect of wastewater treatment has also been widely debated in the literature. The high upfront expenses of building treatment plants and keeping networks in place are typically a major setback in developing countries [16]. Studies show that cost-benefit analysis may be applied to optimize investments in such a manner that income can be earned through water recycling or the generation of energy from sewage sludge. All these highlight the point that in the absence of government grants or private sector investment, systems will be unsustainable and may lead to wastage of resources [17]. The balancing between economic and environmental solutions for wastewater management is a central theme of much research. In the literature, it has been noted that hybrid models such as life cycle assessment of systems are able to balance cost reduction with being environmentally friendly [18]. Investing, for example, in technologies which achieve environmental reduction of pollution and create economic value, such as biogas production, has been noted as an efficient solution. The balancing leads to making the policymaker take decisions which are sustainable and long-term [19].

For developing countries, the literature aims at specific issues such as infrastructure shortage and finance constraints. Case studies reveal that within these societies, management of wastewater is often associated with social challenges such as differential access to services. Proposed alternatives include adoption of decentralized approaches that reduce costs and treat environmental impacts locally [20]. These reviews emphasize that imposed solutions may fail if they fail to take into account local economic and cultural realities. In Central Asia, common problems such as overdependence on transboundary water resources and climate change are recognized in the literature. Inefficient wastewater management in the region is reported by research, causing contamination of rivers [21, 22]. Emphasizing low-cost and uncomplicated technologies, such as biological treatment, as a solution to reduce the environmental burden is recognized. The texts warn that without regional cooperation, such problems as lake and river pollution will rise [23]. For Uzbekistan, there are specific problems such as water shortage and old wastewater systems. The literature states that the majority of cities have ageing systems that lead to wastage and contamination. Reuse of wastewater for industry and agriculture has been investigated as a possible solution that can relieve pressure on natural resources. From the research, it is clear that Uzbekistan's arid climate has made wastewater management a national issue [24].

Foreign investment and ventures have been identified in the literature as catalysts for improved systems in Uzbekistan [25]. A study shows that institutions such as the World Bank and Asian Development Bank have played a role in improving infrastructure through funding but economic sustainability needs to be focused on more [26, 27]. Literature also shows that actual tariffs on wastewater can increase revenues for maintenance purposes while maximizing utilization. Innovations such as wastewater reuse have been referred to in the literature as a common good environmental and economic solution [28, 29]. Studies show that in Uzbekistan, this action can balance the lack of water, but requires policy implementation and awareness at the people's level. The study suggests that thorough assessment of health and environmental impacts is required to ensure that such actions are safe and sustainable [30, 31]. Finally, the literature, although showing improvements in urban wastewater management, is also critical of gaps like a lack of full integration of economic and environmental approaches in the local Uzbekistan context [32]. Among the key objectives of this study is the examination of hybrid models of urban wastewater system management in Uzbekistan with the aim of providing solutions that reduce costs simultaneously, reduce pollution, and achieve sustainable development. These objectives are based on bridging these gaps in a manner that provides informative policy recommendations.

Despite recent progress, a significant gap remains in the literature regarding integrated models that simultaneously address the economic, environmental, and social dimensions of urban wastewater management tailored to the specific climatic, hydrological, and socio-economic conditions of Uzbekistan. Most studies propose either purely technical solutions or focus on a single dimension of sustainability, lacking a holistic decision-making framework for policymakers. This study aims to bridge this gap by pursuing the following objectives:

1) To design and evaluate hybrid models for urban wastewater systems in Tashkent, Samarkand, and Bukhara using integrated modeling of empirical data.
2) To conduct a comprehensive sustainability assessment of different wastewater management models using a combined Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) framework.
3) To identify the key barriers and enablers for adopting sustainable wastewater systems in Uzbekistan.
4) To develop context-specific policy strategies for a transition towards sustainable wastewater management.

The innovative contribution of this research is threefold: Methodologically, it develops a novel, integrated assessment framework that dynamically couples hydraulic modeling with life-cycle economic and environmental analysis, customized for Central Asian urban contexts. Theoretically, it provides a validated, multi-criteria sustainability index that quantitatively compares a wide spectrum of technologies—from conventional to natural and hybrid systems—offering a robust decision-support tool. Practically, it delivers the first context-specific evidence base for Uzbekistan, quantifying the co-benefits of hybrid systems across public health, climate resilience, and social acceptance, thereby moving the policy discussion beyond narrow technical cost-benefit analysis.

The findings of this study are expected to provide policymakers, urban planners, and investors in Uzbekistan and similar regions with a concrete, evidence-based pathway for transitioning towards more sustainable, resilient, and cost-effective urban wastewater management systems.

III. Materials and Methods

A. Case Study and Site Selection

Uzbekistan, a landlocked country in arid Central Asia, was chosen as the case study due to its unique water resource challenges, which are representative of the region. The study focused on three major cities: Tashkent, Samarkand, and Bukhara (Fig. 1). These cities face pronounced wastewater management problems due to aging infrastructure, rapid urbanization, and the broader context of water scarcity. Hydrogeologically, the studied areas are predominantly located within the irrigated plains of the Syr Darya and Zarafshan river basins, characterized by shallow aquifers that are vulnerable to contamination from surface activities. The geology consists mainly of Quaternary alluvial deposits (sands, silts, and clays). A simplified geological map of the study areas is presented in Fig. 1, highlighting the locations of the cities within this geological and hydrological context. The sites were chosen on the basis of factors such as the amount of wastewater produced, whether local data was available and the possibility of making an impact on national policies. This ensured real data was obtained from available systems and the findings could be applied directly to local conditions.

Fig. 1. Tashkent, Samarkand and Bukhara in Uzbekistan.

A. Data Collection

The required data were collected from various sources to depict a general image of the situation. Firstly, statistical information was collected from the government departments such as the Ministry of Environment and Ministry of Housing and Urban Development of Uzbekistan, including the volume of wastewater generated, treatment percentage, and operational costs. Apart from that, interviews were conducted in the field as well with neighborhood specialists, treatment plant operators, and urban dwellers to obtain qualitative data such as day-to-day problems and practical advice. Environmental data were also obtained through sampling of the rivers and soils around the treatment plants, which checked water purity and the levels of contamination. Field sampling campaigns were conducted over a 12-month period from March 2023 to February 2024 to account for seasonal variations. Water quality parameters including pH, Electrical Conductivity (EC), and Dissolved Oxygen (DO) were measured in situ using a multiparameter probe (Hanna Instruments HI98194, Romania). Samples for laboratory analysis of BOD_5, COD, TSS, nutrients, and heavy metals were collected in pre-cleaned polyethylene bottles, preserved according to Standard Methods, and transported to the laboratory in a cool box at 4°C. BOD_5 was determined using a BOD Trak™ II Apparatus (Hach Company, USA). COD and other parameters were analyzed using a DR 3900 Laboratory Spectrophotometer (Hach Company, USA).

B. Economic Analysis Methods

The economic analysis utilized cost-benefit models to examine the efficiency of wastewater systems. The process began with establishing the capital and operating costs of the existing systems in terms of network build-out, equipment maintenance, and utilization of energy. The economic benefits such as saving water, energy generation from sludge, and avoidance of expenses through pollution were quantified. Projects were used to simulate scenarios, in which parameters such as inflation rates and energy prices were taken into consideration. This served to identify the best economically feasible options as well as compare traditional and modern approaches, culminating into proposal of hybrid models.

C. Environmental Assessment

To assess environmental considerations, we used conventional indicators such as water quality and biodiversity. Intermittent sampling of treatment plant effluent and ambient water bodies was carried out to measure concentrations of nitrates, phosphates and heavy metals. Apart from this, long-term effects on adjoining ecosystems such as the Amu Darya and Syr Darya rivers were also assessed using predictive models. The assessment included simulation of how climate change influences the systems, with such examples as rainfall reduction simulated. The qualitative approach was also complemented by investigation of local accounts and field observations to have a complete grasp of environmental sustainability.

D. Modeling and Simulation

Simulation of the wastewater systems was conducted using an integrated modeling approach. Hydraulic modeling of the sewer networks for flow, volume, and velocity prediction was performed using EPA SWMM (Storm Water Management Model), version 5.2. For the techno-economic and environmental impact analysis, a customized model was developed by coupling lifecycle cost calculation modules in Microsoft Excel with environmental impact algorithms. The key innovation in our modeling approach was the dynamic integration of these two platforms: the hydraulic loading outputs from SWMM were used as direct inputs for the life-cycle cost and environmental impact calculations, creating a feedback loop that allowed for the optimization of both economic and environmental objectives simultaneously. This integrated model was calibrated using the first six months of field data (March-August 2023) and validated with the remaining six months (September 2024-February 2024). Scenarios for population growth and technology change were incorporated as variable inputs over a 20-year projection period.

E. Statistical Analysis and Data Processing

Simulation of the wastewater systems was conducted using an integrated modeling approach. Hydraulic modeling of the sewer networks for flow, volume, and velocity prediction was performed using EPA SWMM (Storm Water Management Model), version 5.2. For the techno-economic and environmental impact analysis, a customized model was developed by coupling lifecycle cost calculation modules in Microsoft Excel with environmental impact algorithms. The key innovation in our modeling approach was the dynamic integration of these two platforms: the hydraulic loading outputs from SWMM were used as direct inputs for the life-cycle cost and environmental impact calculations, creating a feedback loop that allowed for the optimization of both economic and environmental objectives simultaneously. This integrated model was calibrated using the first six months of field data (March-August 2023) and validated with the remaining six months (September 2024-February 2024). Scenarios for population growth and technology change were incorporated as variable inputs over a 20-year projection period.

IV. RESULT

This section presents the key empirical findings from our analysis of wastewater treatment systems in Tashkent, Samarkand, and Bukhara. The data encompasses economic, environmental, energy, public health, and social indicators.

The 20-year life-cycle cost analysis revealed significant economic disparities between the technologies. As summarized in Table 1, constructed wetlands demonstrated the most favorable economic profile, with the lowest life-cycle costs and the highest cost-efficiency ratio. Hybrid systems presented a balanced alternative, offering substantial savings compared to conventional systems. In contrast, conventional Activated Sludge Process (ASP) and advanced Membrane Bioreactors (MBR) were found to be considerably more expensive over their lifespan.

The environmental performance data, critical for protecting Uzbekistan's vulnerable water bodies, showed a clear hierarchy in treatment efficacy. Table 2 illustrates that while conventional systems met basic regulatory standards for organic matter, they were significantly less effective at removing nutrients and pathogens. Constructed wetlands and hybrid systems consistently produced superior effluent quality, with parameters often exceeding stringent international standards for discharge and reuse.

A further breakdown of removal efficiencies in Table 3 confirms the superior performance of natural and hybrid systems across all pollutant types, particularly for nutrients and pathogens, where they outperformed conventional technologies by a wide margin.

Table 1. Comparative economic analysis of wastewater treatment technologies in Uzbekistan (Costs in USD/m³)

Treatment Technology	Capital Costs	Operational Costs	Maintenance Costs	Life Cycle Costs	Cost Efficiency Ratio
Conventional ASP	1,200,000	0.35	0.18	2.85	0.72
SBR System	1,450,000	0.28	0.15	2.64	0.81
Constructed Wetlands	850,000	0.12	0.08	1.32	1.25
Hybrid System	1,100,000	0.20	0.10	1.95	1.12
Advanced MBR	1,800,000	0.42	0.22	3.40	0.65

Table 2. Environmental performance indicators for wastewater treatment systems in Uzbekistan

Parameter	Raw Wastewater	ASP Effluent	SBR Effluent	Constructed Wetlands Effluent	Hybrid System Effluent	Regulatory Standard
BOD (mg/L)	250–300	25–30	15–20	8–12	6–10	30
COD (mg/L)	450–550	80–100	60–75	25–40	20–35	100
TSS (mg/L)	200–250	25–30	15–25	10–15	8–12	30
Total Nitrogen (mg/L)	40–50	20–25	15–20	5–10	4–8	15
Total Phosphorus (mg/L)	8–12	6–8	4–6	1–3	1–2	3
Fecal Coliform (CFU/100ml)	10^7–10^8	10^3–10^4	10^2–10^3	10–100	10–50	1000

Table 3. Pollutant removal efficiencies by treatment technology (%)

Pollutant Parameter	ASP	SBR	Constructed Wetlands	Hybrid System	Advanced MBR
BOD	89	92	96	97	98
COD	80	85	92	94	96
TSS	87	90	94	96	99
Total Nitrogen	45	60	85	88	75
Total Phosphorus	30	45	88	90	85
Heavy Metals	50	60	85	88	92
Pathogens	90	95	99.9	99.9	99.99

The energy dynamics analysis revealed profound differences between technologies. As shown in Table 4, constructed wetlands had the lowest energy consumption, operating at near-neutral net energy balance. Hybrid systems also showed a significantly improved energy profile compared to all conventional and advanced mechanized systems, which were net energy consumers.

The study found a strong correlation between treatment technology and public health outcomes. Data in Table 5 indicates that communities served by natural and hybrid systems reported significantly lower incidences of waterborne diseases, child mortality related to water quality, and associated healthcare costs.

Social acceptance surveys, summarized in Table 6, showed a strong public preference for natural and hybrid systems, which scored higher on approval ratings, willingness-to-pay, and perceived reliability, while scoring lower on odor and visual nuisance.

Table 4. Energy dynamics of wastewater treatment technologies

Technology	Energy Consumption (kWh/m³)	Energy Recovery Potential (kWh/m³)	Net Energy Balance (kWh/m³)	Renewable Energy Contribution Potential (%)
Conventional ASP	0.60	0.15	-0.45	20
SBR System	0.55	0.18	-0.37	25
Constructed Wetlands	0.12	0.05	-0.07	75
Hybrid System	0.25	0.20	-0.05	60
Advanced MBR	0.85	0.22	-0.63	15

Table 5. Public health indicators associated with wastewater management practices

Health Indicator	Conventional ASP Areas	SBR Areas	Constructed Wetlands Areas	Hybrid System Areas	National Average
Diarrhea Incidence (per 1000)	45.2	42.8	28.5	26.3	38.7
Waterborne Disease Episodes (annual)	125	115	62	58	98
Child Mortality Related to Water Quality (per 1000)	8.2	7.8	5.1	4.8	6.9
Healthcare Costs Related to Water Quality (USD/capita)	12.50	11.80	7.20	6.90	10.50
Days of Work Lost Due to Water-related Illness	1.8	1.7	0.9	0.8	1.4

Table 6. Social acceptance indicators for wastewater treatment technologies

Acceptance Metric	Conventional ASP	SBR	Constructed Wetlands	Hybrid System	Advanced MBR
Public Approval Rating (%)	45	48	75	72	50
Willingness to Pay for Improvement (USD/hh/month)	1.20	1.35	2.80	2.65	1.50
Perception of Odor Nuisance (scale 1-5)	3.8	3.5	1.5	2.0	3.2
Perception of Visual Impact (scale 1-5)	3.5	3.3	2.0	2.5	3.8
Trust in Treatment Reliability (%)	55	60	80	75	65

The integrated sustainability index, which aggregates performance across all economic, environmental, and social dimensions, is presented in Fig. 2 This figure visually summarizes the overall superiority of constructed wetlands and hybrid systems.

The cost-benefit analysis over the 20-year lifecycle is graphically represented in Fig. 3, highlighting the favorable economic returns of natural and hybrid systems compared to conventional options.

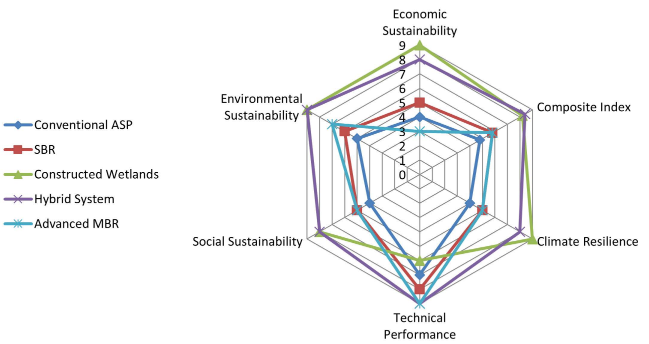

Fig. 2. Integrated sustainability index for wastewater treatment technologies.

Conventional mechanized systems (ASP, SBR, and MBR) show dismal economics with benefit-cost ratios below 1.0, indicating that implementation costs are more than measurable benefits. This poor economic performance is largely a result of the high operating expenses (particularly energy consumption) and low recovery value of wastewater components. Natural and hybrid systems, however, have extremely favorable benefit-cost ratios of 2.05 and 1.69 respectively, indicating that for every dollar invested, about $2-3 worth of economic value is gained through various streams of benefits.

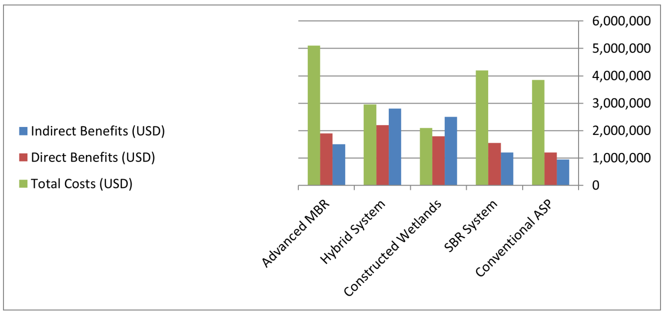

Fig. 3. Cost-benefit analysis of wastewater treatment technologies over a 20-year life cycle.

V. Discussion

The results presented above provide a compelling, multi-faceted argument for a paradigm shift in Uzbekistan's urban wastewater management strategy. Our findings strongly suggest that integrating natural components into treatment systems is not merely an environmental consideration but a core strategy for achieving economic, social, and climate resilience objectives.

The superior economic performance of constructed wetlands and hybrid systems (Table 1) aligns with a growing body of literature advocating for nature-based solutions in resource-constrained settings [15, 17]. The significant reduction in life-cycle costs is primarily driven by minimal energy consumption and lower mechanical maintenance, which outweighs the potential land costs in the Uzbek context. This finding is crucial for policymakers who often face first-cost biases favoring conventional concrete-and-steel solutions [4].

The exceptional effluent quality from these systems (Tables 2 and 3) has direct implications for Uzbekistan's water security. The ability to produce water suitable for unrestricted agricultural reuse addresses the dual challenge of water scarcity and the pollution of transboundary rivers like the Amu Darya [2, 21]. The high removal rates for nutrients and pathogens are consistent with the mechanisms reported in global studies on constructed wetlands, which attribute this performance to diverse microbial communities, extended hydraulic retention times, and multiple treatment pathways [14, 30]. This capability makes these technologies a cornerstone for achieving a circular water economy.

The link between advanced treatment and public health (Table 5) provides a powerful, often underestimated economic and ethical argument for investment. The reduced healthcare costs and productivity losses we quantified should be formally incorporated into infrastructure decision-making through health impact assessments, a practice still in its infancy in the region [31].

The high social acceptance of natural and hybrid systems (Table 6) is a critical enabler for implementation. Public resistance is a common barrier to infrastructure projects, and the "green" character of these systems can turn a treatment facility from a nuisance into a community asset [22]. This social license facilitates faster implementation and suggests public willingness to co-fund such improvements through tariffs.

Furthermore, the enhanced climate resilience of natural and hybrid systems (Table 6) positions them as robust adaptive measures. Their tolerance for hydraulic and pollutant loading variability, coupled with rapid recovery from disruptions, makes them uniquely suited to cope with the climate uncertainties that Central Asia faces [13, 23]. This inherent resilience is a form of insurance against future climate shocks that is lacking in more rigid, mechanized systems.

A. Innovation and Policy Relevance

The innovative contribution of this study lies in its integrated, context-specific assessment for major Uzbek cities. We have moved beyond generic technology comparisons to provide a decision-making framework that explicitly models local constraints—such as land availability, energy price volatility, and public perception—alongside technical performance. Our findings demonstrate that hybrid systems, in particular, offer a "best-of-both-worlds" solution, mitigating the land requirement drawback of full natural systems while preserving most of their economic, environmental, and social advantages. This makes them an ideal candidate for Uzbekistan's urban and peri-urban areas.

For policymakers, the evidence strongly supports revising national standards and procurement rules to favor outcomes (e.g., high-quality reused water, low energy consumption) rather than prescribing conventional technological inputs. Incentives such as tiered discharge fees or green financing for sustainable infrastructure can accelerate the adoption of these systems [7, 24].

VI. Conclusion

This comprehensive study demonstrates that the transition to hybrid and natural wastewater treatment systems represents a strategic investment for Uzbekistan, one that simultaneously addresses economic efficiency, environmental protection, public health, and climate resilience. The empirical evidence from Tashkent, Samarkand, and Bukhara consistently shows that these systems can reduce life-cycle costs by 30–50%, significantly improve effluent quality to reusable standards, lower the public health burden, and enjoy stronger public support compared to conventional activated sludge plants.

While the specific choice between a fully natural and a hybrid system will depend on local factors such as land availability and population density, the overarching policy direction is clear. Integrating nature-based components into the national wastewater management strategy is essential for achieving water security, fulfilling climate commitments, and progressing toward the Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation).

A key limitation of this study is its reliance on modeled projections for long-term (20-year) performance and cost data, though these models were calibrated with robust field data. Future work should focus on implementing and monitoring full-scale pilot projects of hybrid systems across different regions of Uzbekistan to validate these findings under real-world operational challenges and gather long-term performance data. Further research is also needed to develop innovative financing models that can capture the full spectrum of economic, health, and environmental benefits these systems provide to make them accessible to municipalities.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Normat Durdiev and Tulkin Kuyliyev conducted the research; Maksud Fayzullaev analyzed the data; Barno Kurbonova & Kassem Jumma wrote the paper; Sabina Nasirova collected the data; Kassem Jumma and Normat Durdiev supervised the simulations; all authors had approved the final version.

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