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Cost Effective Nature Based Solutions for Urban Water Quality Improvement in Lahore, A Comparative Review

Muhammad Faarid Shah [1, *], Muhammad Waseem [1], Farjad Aziz [1] and Asad Wahab[1]

[1] Department of Civil Engineering (DCvE), Ghulam Ishaq Khan (GIK) Institute of Engineering Sciences and Technology, Topi, Khyber Pakhtunkhwa; gcv2560@giki.edu.pk, muhammad.waseem@giki.edu.pk, gcv2568@giki.edu.pk, gcv2520@giki.edu.pk,

* Correspondence: gcv2560@giki.edu.pk)

Abstract

Rapid urbanization and inadequate wastewater management have intensified water quality degradation in major cities of developing countries, particularly in Lahore, Pakistan. Conventional centralized treatment systems often fail to deliver sustainable performance due to high capital costs, energy dependence and institutional constraints. This study presents a systematic narrative review of cost-effective and sustainable urban water quality improvement methods, with a primary focus on Lahore while maintaining broader applicability across Pakistan. The review evaluates nature-based solutions, low-cost technological interventions, decentralized treatment systems and policy-oriented approaches using a multi-criteria framework encompassing treatment efficiency, cost-effectiveness, environmental sustainability, scalability and contextual suitability. Comparative analysis indicates that constructed wetlands, biochar-based adsorption systems, solar and photocatalytic disinfection technologies and community-based decentralized systems consistently outperform conventional centralized treatment plants under local socio-economic and environmental conditions. Constructed wetlands show high reclamation rates for organic pollutants, biochar systems demonstrate strong heavy-metal removal efficiency and solar-based disinfection offers effective pathogen control under favorable climatic conditions. The findings highlight that no single technology is universally optimal; instead, integrated hybrid treatment configurations aligned with Integrated Urban Water Management principles provide the most viable pathway for sustainable urban water quality improvement. This review offers practical insights for urban planners, policymakers, and water managers seeking resilient, low-cost solutions for rapidly growing cities such as Lahore.

Keywords: Urban water quality management; Nature based solutions; Sustainable water management.

1. Introduction

Safe drinking water is a basic human right and need to survive and live. Consumption of water should not be in the presence of constituents that can have adverse effects on the health of human beings such as toxic minerals, organic compounds and pathogenic microorganisms. Nevertheless, a big percentage of the population in the third world countries still experiences water health issues because of poor access to clean drinking water and microbiological pollution of the water sources [1]. It has been estimated that five million children die each year in developing countries as a result of poor water quality, which is further compounded by the rapid population growth, poor management of water-quality and the overloaded water-supply systems [2]. Poor quality of water is known to cause about 30 percent of all diseases and 40 percent of all deaths in Pakistan [3]. Diarrhea is the most common way of killing the infants and children and approximately 1 out of 5 people experience diseases brought about by the contaminated water [4]. Although these are alarming statistics, there is a little literature on drinking-water quality problem because the policies governing water management in Pakistan still focus on quantity rather than quality. The lack of a national water quality monitoring and surveillance system, inefficient institutional coverage, inadequate laboratories, lack of enforcement of the law and insufficient awareness of the society about water-associated health hazards have also contributed to the crisis [5].

Even though one of the most plentiful renewable resources on Earth is water, the quality and availability of water are slowly getting jeopardized by the processes of population growth, urbanization, industrialization and climate change [6]. This release of untreated industrial effluents and domestic wastewater into surface and underground water systems has had deplorable effects on aquatic life, drinking-water sources and posed serious health risks to the populace due to the accretion of heavy metals and toxic wastes [7], [8]. Inadequate and unreliable water supply in developing nations like Pakistan forces populations to use unsafe water sources such as shallow dug wells and boreholes which exposes them to water borne diseases [9]. There is also emerging research pointing to the fact that the modern water-supplies technologies such as chemical composition of pipelines may contribute to a physical, chemical and biological contamination of drinking water unintentionally [10]. The lack of sufficient supply of safe drinking water, therefore, still remains a significant challenge to the health of people and environmental sustainability.

Water degradation is also especially apparent in large Pakistani cities such as Lahore, where access to sanitation and clean water is very limited and its health effects are very dire. The consumption of polluted water and poor sanitation is leading to one of the most common problems in low-income countries which claims lives of roughly 2.2 million every year. The Sustainable Development Goals (SDGs) have identified that in the global population, some 1.2 billion individuals continue to have no access to basic water services, with most of them being rural inhabitants of Least Developed Countries (LDCs) [11]. Water-borne diseases have caused over 60 per cent of the infant mortality in Pakistan and almost 90 per cent of the rural population in Pakistan has no access to clean drinking water [12]. According to UNICEF, water-related diseases, such as diarrhea, cholera, malaria, hepatitis, typhoid, dysentery and giardiasis are the cause of 12.6 percent neonatal mortality and 7 percent fertility complication-related deaths with an estimated 0.2 to 0.25 million children dying each year due to diarrhea alone [13].

The city of Lahore is the second most populated and 26th largest city in Pakistan and is experiencing a severe and complicated water quality crisis. The climatic variability of the city, which is expressed in the presence of five seasons and an active monsoon phase, also makes a strong impact on the patterns of contamination. Research has reported high levels of physio-chemical measurements, such as total dissolved solids (TDS), pH, calcium (Ca2+), magnesium (Mg2+), turbidity and electrical conductivity (EC) in large residential and urban spaces and in many instances go beyond the World Health Organization (WHO) standards [14]. Aging distribution infrastructure, urban sprawl, inadequate waste management systems, leakage of toxic chemicals and decreasing ground water levels are the causes of these conditions. The Water Quality Index (WQI) evaluation of several Lahore locations indicates that the water quality in the regions is rated as poor (59.66) and very poor (77.30), which highlights the necessity to intervene immediately [14].

Poor treatment of wastewater and poor solid waste management activities are some of the major factors that lead to degradation of water in the city of Lahore [15]. The improper collection of garbage and solid waste encourages infiltration of leachates in the groundwater systems [16]. Reportedly, the concentration of pollutants in landfill sites, such as arsenic has been reported to be in excess of the acceptable levels [15], and discrepancies between the official and informal waste management systems have also been reported to negatively affect the efficiency of waste treatment [17]. Moreover, the further release of the untreated municipal and industrial wastewater into water surfaces increases the environmental pollution and the risk of infections among the population [18], [19]. Unless policy implementation, governance structures, and community involvement improve immediately, the extent of the water quality crisis at Lahore is likely to worsen.

Traditional urban water treatment systems are increasingly becoming pressured by the increasing complexity of pollutants, the accelerated urbanization and climate-related demands. The conventional means of treatment usually do not eliminate new pollutants like pharmaceuticals and microplastics are expensive in operation and consumption and have detrimental byproducts [20], [21]. As a reaction, integrated and sustainable approaches have become prominent. Frameworks such as Integrated Urban Water Management (IUWM) further encourage the management of the whole water cycle as a whole and foster water reuse to make the systems resilient and sustainable [22], [23].

Natural treatment systems specially made wetlands have come out as cheap and energy saving alternative in the treatment of wastewater and in tackling the emerging pollutants [22], [23]. Constructed wetlands (CWs) employ biological, chemical and physical treatment processes to treat wastewater effectively through the use of natural processes. Hybrid CW systems have shown to have high removal efficiency with removal of 92% biochemical oxygen demand (BOD5), 89% chemical oxygen demand (COD) and 97% total suspended solids (TSS) in long-term systems [24]. Equally, the subsurface flow systems in horizontal systems under Mediterranean climates had exhibited mean declines in BOD5 and COD of 55 and 60% respectively [25]. In addition to the treatment, CWs facilitate irrigation through water reuse, improve the aesthetics of urban landscapes, improve microclimates and foster biodiversity, which is in line with the principles of the circular economy [25], [26], [27] . However, there are issues like risks of ground water contamination and their maintenance which should be handled carefully to maximize their performance [26], [28].

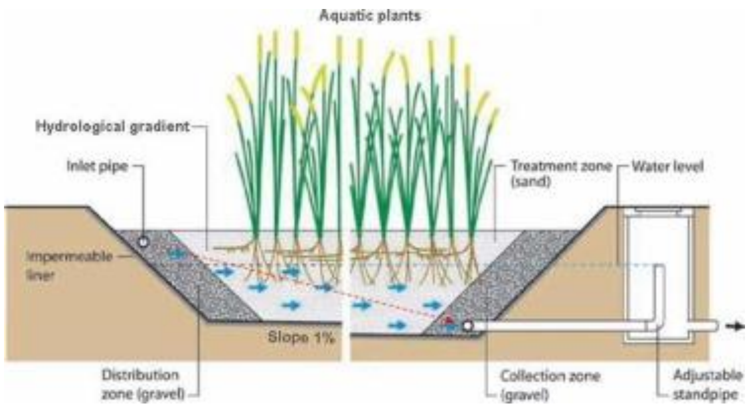

Figure 1: Typical CW Design [29]

Simultaneously, biochar and other inexpensive adsorbents have received some interest due to their usefulness in the removal of heavy metals in polluted water. The biochar will be a cheap and eco-friendly substitute to the normal activated carbon, which is made out of organic waste. The removal of heavy metals happens by the ion exchange, precipitation, complexation and electrostatic interactions with the functional surface groups [30].

Several modified biochars have been reported to have high adsorption capacities with a reported value of 248.33 mg/1 lead and 228.05 mg/1 copper [31], whilst biomass sources such as peanut shells have been reported to have removal efficiencies of upto 90% [32] with reported values of 248.33 mg/1 lead and 228.05 mg/1 copper. Although this has its benefits, more studies are needed on how to maximize the production procedure and improve the adsorption performance to serve large scale use.

Photocatalytic and solar-based disinfection methods also hold a potential remedy to the problem of microbial contamination of wastewater. Solar disinfection is a process that depends on the ultraviolet radiation to inactivate pathogens, which depends on the pH and the presence of oxidizing agents such as hydrogen peroxide[33]. Photocatalytic reactions, especially titanium dioxide-based reactions and doped catalyst-based reactions, yield reactive species in the presence of solar light breaking down organic contaminants and inactivating microorganisms with disinfection yields of up to 100% [34], [35]. Solar concentrators also increase the efficiency of the treatment and minimizes the costs of operation [36]. Nevertheless, issues concerning the changing sunlight supply and complicated wastewater compositions require further optimization.

Community-based and decentralized water treatment systems provide further avenues to the idea of sustainable water management, especially in regions where centralized water treatment infrastructure is either scarce or not economical. These systems save capital, lessen the amount of energy necessary in the transportation of wastewater and foster localized consumption of resources [37]. Enhancing the elimination of the pollutants at the subsystem level, decentralized systems will lead to environmental sustainability and provide water reuse and nutrient recovery in a circular economy model [38], [39]. Community participation also increases the ownership, accountability and long-term performance of the system yet regulatory, technical and social obstacles are still a big hurdle [38], [40].

Last but not least, ineffective water quality management is still limited by persistence of policy and governance gaps. Sustainable water governance suffers as a result of inconsistent legal frameworks, lack of coordination between institutions, financial transparency and lack of public involvement [41], [42], [43]. There is a need to create an integrated policy that closes urban-rural and sectoral gaps that can help mitigate these failures and promote collaborative and holistic management strategies [44]. The solution of the governance issues, as well as the technological and nature-based solutions, is important to attain long-term enhancements in the quality of urban water.

2. Methodology

2.1. Study Area

Lahore, the capital city of Punjab province (Figure 2), is a fast-urbanizing city where water quality issues are an important concern because of the large population density, industrialization, and poor wastewater systems [14], [15]. Having a population more than 11 million people and an area of 1137.43Km2, the city undergoes significant municipal wastewater production, stormwater runoff and surface and groundwater resources pollution [14], [15]. These circumstances precipitate the urgent requirement of cost-efficient and sustainable water treatment systems to be employed within financial, institutional as well as land-use limitations that are inherent in Lahore.

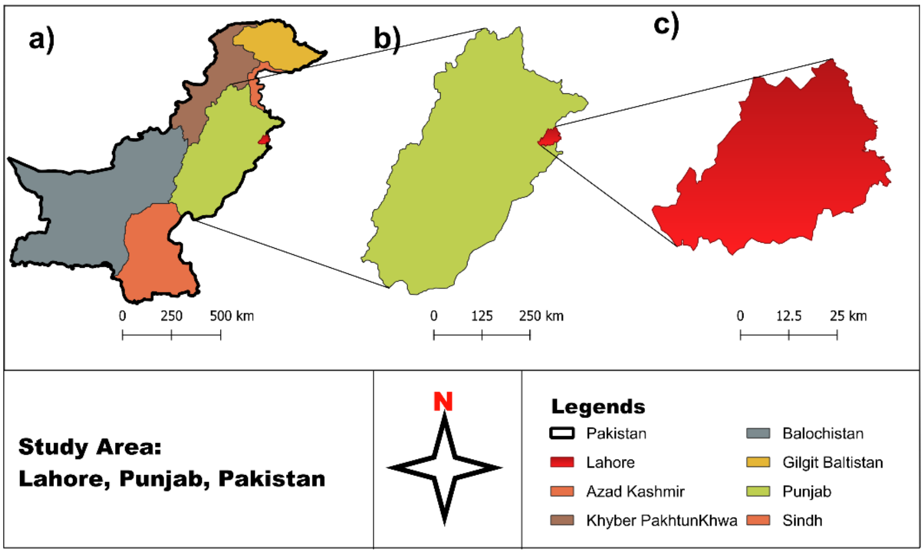

Figure 2: Map of study area showing a) Boundaries of Pakistan with its provinces, b) Boundaries of Punjab & c) Study area, Lahore.

2.2 Design and Analytical Framework

This review paper has assumed a systematic narrative review approach of assessing cost-effective and sustainable strategies of enhancing the water quality in cities, with a specific focus to developing countries like Lahore, Pakistan. Instead of producing new experimental data, the approach is concerned with the synthesis of empirical, applied and policy-oriented studies to find treatment options that are technically efficient, economically viable and environmentally friendly under urban conditions that are constrained by resources [21], [23]. The analysis is informed by the principles of the Integrated Urban Water Management (IUWM) and sustainable management of water resources, including decentralized pollution control, optimal use of resources and adjustment to climate changes, as well as adaptive governance in rapidly urbanizing conditions. Through a combination of the principles, the review allows making a well-balanced comparison between nature-based solutions and low-cost technological interventions in various performance aspects that are frequently found in Pakistan and other developing economies.

2.3 Evaluation criterion and comparative assessment.

In order to have uniformity in the heterogeneous treatment technologies, a multi-criteria assessment model was elaborated that includes the technical, economic, environment, and contextual dimensions. The efficiency of the treatment commonly called the reclamation rate was considered in studies that reported the system performance in the long-term or full-scale system, as these give more indicators of operational effectiveness than short-term laboratory studies. The indicators used to measure economic performance did not consider monetary values, but relative cost, since there is a large variation in construction, labor and energy costs across the region. Technologies were thus evaluated according to capital concentration, operational and maintenance needs, energy reliance and use of locally manufactured and imported materials. This type of comparative cost classification is widely used in sustainability-oriented water treatment reviews and allows us to make cross-context comparisons without the bias related to currencies . Environmental sustainability was considered via such indicators as energy use, implications of greenhouse gas emissions, water reuse potential and the correspondence to the principles of the circular economy. Environmentally friendly technologies included those that depend on passive methods of treatment, renewable sources of energy, or waste products. Social and ecological co-benefits like improvement in biodiversity, landscape incorporation and acceptance by the community were also included in the evaluation where reported. Contextual suitability was determined through the association of each method of treatment in relation to the particular urban water quality issues such as: municipal wastewater pollution, stormwater run off, contaminated ground water with heavy metals and microbiologically unsafe drinking water. The evaluation, which is problem-oriented, would be in line with IUWM principles and adaptive urban water governance frameworks [22], [23].

2.4 Tabular Comparative Analysis of Treatment Methods.

Table 1 gives a plotted comparison of the urban water quality improvement methods in Lahore, Pakistan under the parameters of efficiency of treatment, cost-effectiveness, environmental sustainability, feasibility and scalability, social acceptance, policy alignment and general suitability. The tabular evaluation will allow making a direct comparison between nature-based, technological, decentralized and governance-related interventions and will offer a systematized foundation of interpretation of the relative merits and the constraints of the Pakistani situation. As noted in the table, the constructed wetlands are highly effective in organic pollution and suspended solids removal, the biochar-based adsorbents are highly effective in removing heavy-metal, solar and photocatalytic systems are highly effective in inactivating pathogens and decentralized systems are flexible and scalable in infrastructure-constrained environments. The indirect impact of policy and governance interventions on water quality is enabled by facilitating better performance of the system, compliance and long-term sustainability.

2.5 Comparative Findings Interpretation in Lahore, Pakistan.

The comparative analysis Table 1 suggests that solutions based on nature and low cost that are decentralized, persistently perform better as compared to conventional centralized systems in comparison with Pakistan-specific economic, infrastructural, and administrative constraints. Wetlands on construction exhibit a high reclamation of organic and suspended solids and have very low operational expenses and energy needs, which makes them very appropriate in the treatment of urban water waste in cities like Lahore [24], [26]. Their effects on the environment are mostly positive because of the improvement of the ecosystem and the minimization of greenhouse gas emissions in comparison with mechanical treatment systems [25], [28]. Adsorption systems that use biochar become one of the most successful alternatives in the treatment of heavy-metal-contaminated groundwater, which is becoming a more and more serious problem in Pakistan in the context of the industrial discharge and landfill leachate intrusion [15], [31]. Their low pricing, use of agricultural residues and high adsorption results are in line with the circular economy targets and national sustainability targets [30], [32]. Solar and photocatalytic disinfection systems exhibit almost 100 percent pathogen elimination when the standard solar conditions are favorable and are thus quite useful in dealing with microbiological contamination of drinking water in Pakistani high-solar environment. Decentralized treatment systems of wastewater also provide resilience and flexibility particularly in regions that do not have a centralized infrastructure, although their effectiveness depends on the proper design and maintenance of the system [37], [40].

Conversely, traditional centralized treatment facilities have remained limited to high capital, energy reliance and operational inefficiencies, despite their high theoretical performance, which lowers their effectiveness in the long run in urban settings in Pakistan [18], [19].

Table 1: Comparative Findings in context of Lahore

Method	Treatment Efficiency	Cost-Effectiveness	Environmental Sustainability	Feasibility / Scalability	Social / Community Acceptance	Policy / Regulatory Alignment	Overall Suitability in Pakistan
Constructed Wetlands (CW)	**High** for BOD, COD, and TSS; **Moderate** for pathogen removal (up to 90%)	**Moderate**; low operational costs but high land requirement	**High**; natural processes, minimal energy use, low carbon footprint	**Moderate**; land-intensive, limiting dense urban deployment	**High**; strong potential for community involvement	**Moderate**; Requires supportive land-use and wastewater policies	**Suitable** for Peri-urban and low-density areas
Biochar / Low-Cost Adsorbents	**High**; effective for heavy metals and organics (up to 90%)	**High**; low-cost, reusable, locally sourced materials	**High**; promotes circular economy and waste valorization	**High**; modular, scalable, and adaptable	**Moderate**; basic technical training required	**Moderate**; regulatory support needed for reuse and disposal	**Highly suitable** for urban and peri-urban treatment
Solar / Photocatalytic Disinfection	**High** for pathogens; **Moderate** for organics (up to 100% inactivation)	**Moderate**; higher initial cost but low operational expenses	**High**; solar-powered and environmentally clean	**Moderate**; dependent on sunlight and catalyst maintenance	**Moderate**; requires training and monitoring	**Moderate**; compliance with drinking water standards required	**Suitable** for point-of-use potable water treatment
Community-Based / Decentralized Systems	**Moderate to High**; technology-dependent performance	**High**; avoids centralized infrastructure costs	**High**; localized treatment reduces energy and discharge	**High**; flexible across settlement types	**High**; strong community ownership and participation	**Moderate to High**; supports decentralized governance	**Highly suitable** for informal and resource-limited communities
Policy / Governance Interventions	**Indirect Impact**; strengthens all technical solutions	**Not Directly Applicable**; focused on regulation and enforcement	**High**; enables sustainable practices and incentives	**High**; provides a framework forscaling interventions	**High**; promotes accountability and public engagement	**High**; essential for coordination and legal compliance	**Critical** across urban and rural settings

2.6 Methodological Implications.

The comparative evaluation has shown that there is no one optimum treatment technology that offers universal solution. Rather, hybrid treatment designs which take into account the combined use of constructed wetlands, biochar filtration and solar-based disinfection, represent the most balanced treatment based on cost, performance, sustainability and environmental impact indicators. These combined strategies comply with concepts of IUWM and constitute a viable way of sustainable urban enhancement of water quality in Pakistan

3. Results

The findings of the comparative analysis indicate that urban water quality improvement methods portray some specific performance trends when evaluated regarding the treatment effectiveness, cost, sustainability and contextual suitability. On the whole, the nature-based and decentralized systems prove to be more effective compared to the centralized ones given the financial, institutional, and infrastructural limitations that Pakistani cities like Lahore have to operate.

3.1 Treatment Efficiency and Reclamation Performance

In general, constructed wetlands had high reclamation rates of organic and suspended solids, and BOD5, COD, and TSS removal efficiencies were reported to be usually over 85 and, in other longer-term systems, higher than 90 percent [24], [25], [26]. Their results are affirmative that they are applicable in the municipal wastewater treatment in Pakistan where organic pollution is still a major issue of concern [14], [15].

The adsorption systems that were constructed with biochar demonstrated good and consistent capabilities of the removal of heavy-metals, with efficiencies generally in the range of 70 to 90 percent of removed contaminants including lead, cadmium, copper and zinc [30], [31], [32]. The solar and photocatalytic disinfection technologies had the best reclamation of microbial contaminants with a pathogen inactivation efficacy of up to 100 percent when the solar conditions were favorable [33], [35]. Centralized treatment plants on the contrary showed uneven real-life performance in terms of operational failures, energy shortage, and failure to maintain the system, especially in big urban areas [18], [19].

3.2 Cost Performance and Economic Feasibility.

The cost proved to be a critical factor that affected technology feasibility. Biochar-based and constructed wetlands were always categorized as low-cost alternatives because they were built with the use of the locally available resources and used passive treatment mechanisms and consumed low energy [26], [30]. Solar disinfection systems were divided into low-to-moderate cost categories, where the initial investment in infrastructure is compensated by insignificant operating costs over a period [33], [36].

At the community scale, decentralized wastewater systems have shown desirable performance in terms of costs since they minimize the cost related to conveyance infrastructure and allow them to operate at a local scale [37], [40]. On the other hand, centralized treatment plants were characterized by high costs of capital and operation induced by the energy-consuming processes and multicomponent maintenance needs, which greatly reduces their scalability in Pakistan.

3.3 Sustainability and Impact to the environment.

Nature based solutions were much better in performance. Wetlands built helped to increase biodiversity, enhance microclimates and use of non-drinkable water and had low carbon footprint. The biosystems have facilitated the goals of waste valorization and circular economy through the utilization of agricultural residues to generate operational treatment media.

There were insignificant systems on solar disinfection technology which revealed insignificant environmental impact through the removal of chemical disinfectants and the use of fossil fuel-based energy. Decentralized systems were also more sustainable with the incentive to local ownership encouraging low infrastructure load and resilience to climate induced water stress. Centralized systems in turn were also linked with increased environmental impact such as greenhouse gases and sludge management issues.

3.4 Contextual Suitability

A comparison of the results with the various water quality issues facing Pakistan reveals that integrated treatment structures are the most suitable performance systems compared to single technologies. The most flexible system to the Pakistani fractured urban infrastructure and mixed profiles of contamination is the hybrid system with nature-based and cheap technological interventions, as described in Table 1.

4. Discussion

The findings underscore the importance of aligning urban warer treatment technologies with local economic, institutional and environmental conditions rather than relying solely on conventional centralized systems. While centralized treatment plants offer theoretical advantages in terms of capacity and standardized control, their effectiveness in Lahore, Pakistan is constrained by unreliable energy supply, high operational costs and limited technical expertise. These limitations reduce long-term system reliability and sustainability.

Nature-based solutions, particularly constructed wetlands, provide multiple co-benefits beyond wastewater treatment, including ecosystem enhancement, climate adaptation and water reuse opportunities. However, their primary limitation lies in land requirements, which may restrict large-scale deployment in densely populated urban cores. Biochar-based adsorption systems offer flexibility and effectiveness for heavy-metal removal but require periodic regeneration or replacement of media, necessitating proper waste handling strategies.

Solar and photocatalytic disinfection technologies are highly effective for pathogen removal and are especially suitable for regions with high solar irradiance. Their performance, however, may fluctuate under unfavorable weather conditions, indicating the need for hybrid integration with complementary treatment methods. Decentralized systems address infrastructure and governance challenges by enabling community-level management, though their success depends on institutional support, public awareness and capacity building.

The methodological framework applied in this study is transferable to other developing urban contexts facing similar constraints, such as cities in South Asia, Africa and Southeast Asia. Integrating performance indicators related to efficiency, cost and sustainability enables decision-makers to identify context-specific solutions rather than adopting uniform treatment strategies.

From a policy perspective, the results suggest that urban water management strategies should prioritize hybrid and decentralized treatment models, supported by regulatory incentives, land-use planning integration and capacity-building initiatives. Policymakers should encourage public-private partnerships, promote the reuse of treated wastewater, and incorporate nature-based solutions into urban development plans to enhance long-term water security.

5. Conclusions

This study demonstrates that nature-based and decentralized wastewater treatment systems offer more effective, economically viable and environmentally sustainable solutions for improving urban water quality in Lahore and similar cities. Constructed wetlands, biochar-based adsorption systems and solar disinfection technologies outperform centralized treatment plants under prevailing financial and institutional constraints.

The adoption of integrated hybrid systems that combine natural and low-cost technological approaches provides a practical pathway for addressing diverse pollution profiles and fragmented urban infrastructure. Future urban water policies in Pakistan should emphasize decentralized governance, sustainable financing mechanisms and the integration of nature-based solutions to achieve resilient and inclusive water quality management.

References

[1] F. X. R. Van Leeuwen, "Safe drinking water: the toxicologist's approach," *Food and Chemical Toxicology*, vol. 38, pp. S51–S58, 2000.

[2] G. H. Huang and J. Xia, "Barriers to sustainable water-quality management," *Journal of environmental management*, vol. 61, no. 1, pp. 1–23, 2001.

[3] D. S. Asia, "Water vision 2025, country report, Pakistan. Maharashtra, India, global water partnership," *South Asia Technical Advisory Committee Regional Office*, 2000.

[4] M. A. Kahlown, M. A. Tahir, H. Rasheed, and K. P. Bhatti, "Water quality status, national water quality monitoring programme," *Fourth Tech ReportPCRWR*, vol. 5, 2006.

[5] J. A. Aziz, "Management of source and drinking-water quality in Pakistan," *East Mediterr Health J*, vol. 11, no. 5–6, pp. 1087–1098, 2005.

[6] R. Nawaz *et al.*, "Water quality index and human health risk assessment of drinking water in selected urban areas of a Mega City," *Toxics*, vol. 11, no. 7, p. 577, 2023.

[7] M. A. Irshad, M. B. Shakoor, S. Ali, R. Nawaz, and M. Rizwan, "Synthesis and Application of Titanium Dioxide Nanoparticles for Removal of Cadmium from Wastewater: Kinetic and Equilibrium Study," *Water Air Soil Pollut*, vol. 230, no. 12, p. 278, Dec. 2019, doi: 10.1007/s11270-019-4321-8.

[8] M. A. Irshad *et al.*, "Green and eco-friendly synthesis of TiO_2 nanoparticles and their application for removal of cadmium from wastewater: reaction kinetics study," *Zeitschrift für Physikalische Chemie*, vol. 236, no. 5, pp. 637–657, May 2022, doi: 10.1515/zpch-2021-3171.

[9] M. Varol and C. Tokatlı, "Evaluation of the water quality of a highly polluted stream with water quality indices and health risk assessment methods," *Chemosphere*, vol. 311, p. 137096, 2023.

[10] M. K. Daud *et al.*, "Drinking Water Quality Status and Contamination in Pakistan," *BioMed Research International*, vol. 2017, pp. 1–18, 2017, doi: 10.1155/2017/7908183.

[11] "SDG Indicators." Accessed: Nov. 08, 2025. [Online]. Available: https://unstats.un.org/sdgs/report/2022/goal-06/

[12] S. Perveen, "Drinking water quality monitoring, assessment and management in Pakistan: A review," *Heliyon*, vol. 9, no. 3, 2023, Accessed: Nov. 08, 2025. [Online]. Available: https://www.cell.com/heliyon/fulltext/S2405-8440(23)01079-4

[13] "Pakistan Population 2025." Accessed: Nov. 08, 2025. [Online]. Available: https://worldpopulationreview.com/countries/pakistan

[14] M. Latif *et al.*, "Assessment of drinking water quality using Water Quality Index and synthetic pollution index in urban areas of mega city Lahore: a GIS-based approach," *Sci Rep*, vol. 14, no. 1, p. 13416, Jun. 2024, doi: 10.1038/s41598-024-63296-1.

[15] A. Malik Muhammad and T. Zhonghua, "Municipal Solid Waste and its Relation with Groundwater Contamination in Lahore, Pakistan," *RJASET*, vol. 7, no. 8, pp. 1551–1560, Feb. 2014, doi: 10.19026/rjaset.7.431.

[16] F. Ayub, S. L. H. Naqvi, S. H. Z. Naqvi, A. Yasar, R. Akram, and J. Niamat, "Assessment of Municipal Solid Waste Management Practices in Urban Centers of Pakistan: A Comprehensive Review," *Environmental Protection Research*, pp. 87–103, May 2024, doi: 10.37256/epr.4120244086.

[17] I. U. Khan, W. A. Waseer, S. Ullah, and S. A. Khan, "'Wasteaware' Indicators: an Assessment of the Current Solid Waste Management System in Lahore, Pakistan," *Asia Pac. j. energy environ.*, vol. 5, no. 2, pp. 49–58, 2018, doi: 10.18034/apjee.v5i2.525.

[18] A. Jabeen, X. Huang, and M. Aamir, "The Challenges of Water Pollution, Threat to Public Health, Flaws of Water Laws and Policies in Pakistan," *JWARP*, vol. 07, no. 17, pp. 1516–1526, 2015, doi: 10.4236/jwarp.2015.717125.

[19] M. Basharat and S. A. Rizvi, "Groundwater extraction and waste water disposal regulation. Is Lahore Aquifer at stake with as usual approach," in *Pakistan Engineering Congress, World Water Day, Lahore*, 2011, pp. 112–134. Accessed: Nov. 08, 2025. [Online]. Available: https://www.pecongress.org.pk/images/upload/books/Ground%20Water%20Extraction%20and%20Waste%20Water%20Disposal%20Regulation%20.pdf

[20] T. Sahu, "Meta-Analysis of Global Water Contaminants and Chemical Treatment Techniques," in *Green Chemistry, Nanotechnology, and Sustainable Materials for Climate Action and Circular Economy*, Deep Science Publishing, 2025, pp. 121–129. doi: 10.70593/978-93-7185-662-1_13.

[21] S. Stoll and S. R. Gentile, "Urban water quality and chemical pollution," in *Routledge Handbook of Urban Water Governance*, 1st ed., London: Routledge, 2022, pp. 374–386. doi: 10.4324/9781003057574-31.

[22] G. Alaerts and N. Dickinson, Eds., "Challenges for urban water supply and sanitation in developing countries," in *Water for a Changing World - Developing Local Knowledge and Capacity*, 0 ed., CRC Press, 2008, pp. 93–112. doi: 10.1201/9780203878057-12.

[23] K. Vairavamoorthy, J. Eckart, S. Tsegaye, K. Ghebremichael, and K. Khatri, "A Paradigm Shift in Urban Water Management: An Imperative to Achieve Sustainability," in *Sustainability of Integrated Water Resources Management*, S. G. Setegn and M. C. Donoso, Eds., Cham: Springer International Publishing, 2015, pp. 51–64. doi: 10.1007/978-3-319-12194-9_4.

[24] G. Martel-Rodríguez, V. Millán-Gabet, C. Mendieta-Pino, E. García-Romero, and J. Sánchez-Ramírez, "Long-Term Performance of a Hybrid-Flow Constructed Wetlands System for Urban Wastewater Treatment in Caldera de Tirajana (Santa Lucía, Gran Canaria, Spain)," *IJERPH*, vol. 19, no. 22, p. 14871, Nov. 2022, doi: 10.3390/ijerph192214871.

[25] O. A. Samodolova, A. P. Samodolov, D. V. Ulrikh, and M. N. Bryukhov, "Using Constructed Wetlands to Clean Wastewater from Various Sources," in *Proceedings of the 7th International Conference on Construction, Architecture and Technosphere Safety*, vol. 400, A. A. Radionov, D. V. Ulrikh, S. S. Timofeeva, V. N. Alekhin, and V. R. Gasiyarov, Eds., in Lecture Notes in Civil Engineering, vol. 400. , Cham: Springer Nature Switzerland, 2024, pp. 578–584. doi: 10.1007/978-3-031-47810-9_53.

[26] S. Kumar, B. Pratap, D. Dubey, and V. Dutta, "Integration of Constructed Wetland Technology as Decentralized Wastewater Treatment Facility and Water Reuse in Agriculture," in *Environmental Studies and Climate Change*, 1st ed., New York: CRC Press, 2022, pp. 565–582. doi: 10.1201/9781003220824-39.

[27] T. Li and Y. Huang, "Wastewater Treatment Appliances for Urban Constructed WQT Wetland Landscaping," in *Advances in Transdisciplinary Engineering*, X. Zhang, H. Ren, Y. Lu, and C. Wang, Eds., IOS Press, 2022. doi: 10.3233/ATDE220329.

[28] A. Acero-Oliete, P. L. López-Julián, B. Russo, and O. Ruiz-Lozano, "Comparative Efficiency of Two Different Constructed Wetlands for Wastewater Treatment of Small Populations in Mediterranean Continental Climate," *Sustainability*, vol. 14, no. 11, p. 6511, May 2022, doi: 10.3390/su14116511.

[29] M. Wang, D. Q. Zhang, J. W. Dong, and S. K. Tan, "Constructed wetlands for wastewater treatment in cold climate — A review," *Journal of Environmental Sciences*, vol. 57, pp. 293–311, Jul. 2017, doi: 10.1016/j.jes.2016.12.019.

[30] B. K. Biswal and R. Balasubramanian, "Use of biochar as a low-cost adsorbent for removal of heavy metals from water and wastewater: A review," *Journal of Environmental Chemical Engineering*, vol. 11, no. 5, p. 110986, Oct. 2023, doi: 10.1016/j.jece.2023.110986.

[31] H. A. Al-Swadi *et al.*, "Kaolinite-Composited Biochar and Hydrochar as Low-Cost Adsorbents for the Removal of Cadmium, Copper, Lead, and Zinc from Aqueous Solutions," *Sustainability*, vol. 15, no. 22, p. 15978, Nov. 2023, doi: 10.3390/su152215978.

[32] T. I. K. Mathabatha, A. N. Matheri, and M. Belaid, "Peanut Shell-Derived Biochar as a Low-Cost Adsorbent to Extract Cadmium, Chromium, Lead, Copper, and Zinc (Heavy Metals) from Wastewater: Circular Economy Approach," *Circ.Econ.Sust.*, vol. 3, no. 2, pp. 1045–1064, Jun. 2023, doi: 10.1007/s43615-022-00207-4.

[33] C. M. Núñez-Núñez, G. I. Osorio-Revilla, I. Villanueva-Fierro, C. Antileo, and J. B. Proal-Nájera, "Solar Fecal Coliform Disinfection in a Wastewater Treatment Plant by Oxidation Processes: Kinetic Analysis as a Function of Solar Radiation," *Water*, vol. 12, no. 3, p. 639, Feb. 2020, doi: 10.3390/w12030639.

[34] J. A. Byrne, P. A. Fernandez-Ibañez, P. S. M. Dunlop, D. M. A. Alrousan, and J. W. J. Hamilton, "Photocatalytic Enhancement for Solar Disinfection of Water: A Review," *International Journal of Photoenergy*, vol. 2011, pp. 1–12, 2011, doi: 10.1155/2011/798051.

[35] A. C. Mecha, M. S. Onyango, A. Ochieng, and M. N. B. Momba, "UV and solar photocatalytic disinfection of municipal wastewater: inactivation, reactivation and regrowth of bacterial pathogens," *Int. J. Environ. Sci. Technol.*, vol. 16, no. 7, pp. 3687–3696, Jul. 2019, doi: 10.1007/s13762-018-1950-1.

[36] J. S. Roy and Y. Messaddeq, "The Role of Solar Concentrators in Photocatalytic Wastewater Treatment," *Energies*, vol. 17, no. 16, p. 4001, Aug. 2024, doi: 10.3390/en17164001.

[37] D. Milićević, M. Milićević, and R. Trajković, "DECENTRALIZED WASTEWATER TREATMENT - A SUSTAINABLE SOLUTION FOR PROTECTING WATER RESOURCES FROM POLLUTION," *ZRGAF*, vol. 39, no. 1, pp. 35–46, Jun. 2024, doi: 10.62683/zrgaf39.35-46.

[38] H. N. Giwa, H. O. Giwa, S. O. Alepu, W. Zelong, and A. S. Giwa, "Decentralization of Household Wastewater Streams: Challenges and Perspectives," *Collect J Environ Sci*, pp. 01–06, Jun. 2024, doi: 10.70107/collectjenvironsci-ART0011.

[39] C. Ramprasad and S. Rangabhashiyam, "The role of sustainable decentralized technologies in wastewater treatment and reuse in subtropical Indian conditions," in *Water Conservation and Wastewater Treatment in BRICS Nations*, Elsevier, 2020, pp. 253–268. doi: 10.1016/B978-0-12-818339-7.00012-6.

[40] J. M. D. S. Vieira, L. B. Villanova, M. V. Filho, R. M. Mendes, and C. Gomes, "Implementation of Decentralized Sanitation Systems with Nature-Based Technologies: Advantages and Challenges in Rural Areas, Slums and Urban Communities," *JER*, vol. 4, no. 22, pp. 2–14, Aug. 2024, doi: 10.22533/at.ed.3174222421083.

[41] C. H. C. Hafizan *et al.*, "Addressing Gaps in Water Protection Law for River Conservation," *Environmental Claims Journal*, vol. 36, no. 2, pp. 141–168, Apr. 2024, doi: 10.1080/10406026.2024.2394920.

[42] C. Mateus, M. Valencia, K. DiFrancesco, V. Ochoa-Herrera, T. Gartner, and D. Quiroga, "Governance Mechanisms and Barriers for Achieving Water Quality Improvements in Galapagos," *Sustainability*, vol. 12, no. 21, p. 8851, Oct. 2020, doi: 10.3390/su12218851.

[43] M. A. Islam and S. L. Islam, "Impact of climate change on water quality and public policy approach to reduce uncertainty and risk," in *Handbook of Water Purity and Quality*, Elsevier, 2021, pp. 57–75. doi: 10.1016/B978-0-12-821057-4.00009-4.

[44] A. Drevno, "From Fragmented to Joint Responsibilities: Barriers and Opportunities for Adaptive Water Quality Governance in California's Urban-Agricultural Interface," *Resources*, vol. 7, no. 1, p. 22, Mar. 2018, doi: 10.3390/resources7010022.