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A Systems-Based Framework for Sustainable Environmental Solutions: Integrating Science, Technology, and Policy for Resilience and Resource Efficiency

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ABSTRACT

Urban environments in rapidly developing regions face mounting challenges related to water contamination, environmental degradation, and inadequate infrastructure. This study introduces a Systems-Based Framework for Environmental Sustainability (SIES) that integrates scientific water quality monitoring, low-cost purification technologies, stakeholder engagement, and policy alignment. Implemented across five sites in Pune, India, the framework combined biosand filtration and solar disinfection (SODIS) to address biological and chemical water pollutants. Water quality assessments before and after intervention revealed significant reductions in biochemical oxygen demand (−69.8%), chemical oxygen demand (−71.7%), *E. coli* (−90.4%), and heavy metals (−60–70%). In addition to technical outcomes, the study engaged residents, local authorities, and NGOs to evaluate the social acceptability and scalability of the solution. Stakeholder interviews revealed 83% satisfaction with water quality and 76% noting improved health outcomes. A Multi-Criteria Decision Analysis (MCDA) ranked the SIES approach highest among alternative water treatment strategies based on environmental impact, cost, acceptability, and policy compatibility. Importantly, the results were adopted by the local municipal board, demonstrating early policy integration of decentralized water treatment systems. This study demonstrates that integrated, community-informed environmental models can deliver scalable and sustainable improvements in water security. The findings underscore the value of bridging science, technology, and policy to enhance urban resilience in the face of ecological and public health threats.

Keywords: Integrated environmental management, Sustainable water treatment, Bios and filter, Urban resilience, Science–policy interface, Community engagement, Water quality, Environmental sustainability

INTRODUCTION:

Environmental degradation has reached critical levels across the globe, driven largely by industrialization, unplanned urban expansion, resource overconsumption, and weak institutional governance. The increasing frequency of climate-induced events such as extreme weather, droughts, and biodiversity collapse reflects the planetary-scale consequences of human-induced disruption of Earth systems (Steffen et al., 2015). Despite the wealth of environmental knowledge and technological advances, the absence of coordinated and systemic approaches continues to undermine progress toward long-term sustainability.

Conventional environmental solutions have traditionally emerged from discipline-specific silos—environmental chemistry to monitor pollution, civil engineering to build infrastructure, and political science to design regulatory mechanisms. However, such fragmented interventions often fail to address the complexity of socio-ecological systems, where feedback loops between the environment, technology, and governance must be understood and managed holistically (Liu et al., 2007). This has led to a growing demand for interdisciplinary and systems-based approaches that integrate scientific inquiry, technological innovation, and policy formulation under a unified sustainability framework.

The United Nations' Sustainable Development Goals (SDGs), particularly SDG 6 (clean water and sanitation), SDG 11 (sustainable cities), and SDG 13 (climate action), explicitly emphasize the interconnectivity of environmental, technological, and institutional pathways (United Nations, 2015). However, translating these broad objectives into local, actionable strategies remains a global challenge, particularly in rapidly urbanizing regions where infrastructure, environmental data systems, and regulatory enforcement are often lacking.

RATIONALE FOR INTEGRATION:

While innovations in environmental science and technology have made it possible to detect, model, and treat pollutants at finer scales, such tools are often underutilized or remain confined to research laboratories. Without corresponding policy mechanisms, even well-validated technologies fail to achieve real-world impact. Similarly, policy frameworks that are disconnected from environmental monitoring data or stakeholder feedback tend to lack legitimacy and effectiveness (Cash et al., 2003). This disconnect between science, technology, and policy significantly hampers the scalability and sustainability of environmental interventions.

The concept of the science–policy–technology nexus seeks to bridge these institutional and epistemological divides. It aims to create feedback loops where scientific evidence informs technological applications, policy supports innovation, and societal engagement ensures equity and relevance (van den Hove, 2007). This model supports **co-produced solutions**, where stakeholders across disciplines and sectors collaborate throughout the process—from problem identification to solution deployment and policy integration (Mauser et al., 2013).

One of the most promising operational tools to support such integration is the systems approach, which considers interrelated components, feedback loops, trade-offs, and synergies across environmental and socio-technical systems. Systems thinking has been successfully applied in water–energy–food nexus studies (Weitz et al., 2017), integrated coastal zone management (Kay & Alder, 2005), and circular economy frameworks (Geissdoerfer et al., 2017). However, most models lack a practical structure for incorporating low-cost technologies and inclusive policy mechanisms, especially in developing contexts.

Research Gap and Study Objectives:

Despite the theoretical acceptance of integrative approaches in sustainability science, there remains a critical gap in their operationalization at the local scale. Existing sustainability models are often either too technically sophisticated for under-resourced communities or too generic to offer precise, data-driven recommendations. There is a pressing need for frameworks that are:

Scientifically rigorous

Technologically feasible

Economically viable

Socially acceptable

Politically implementable

To address this gap, the present study proposes a Systems-Based Framework for Environmental Sustainability (SIES). The model integrates real-time environmental monitoring, decentralized water treatment technologies, and stakeholder-informed policy feedback mechanisms into a replicable, low-cost structure.

The research was conducted using a case study approach in Pune, India, an urban region facing acute water quality challenges due to industrial discharge, poor sanitation infrastructure, and regulatory lapses. The study aims to:

Develop a systems framework that aligns scientific monitoring, technological solutions, and policy design.

Deploy and assess the performance of affordable water purification interventions.

Engage stakeholders to evaluate the feasibility, equity, and scalability of the integrated approach.

Provide a transferable model for municipalities and institutions aiming to align environmental goals with social and governance contexts.

Novelty and Significance:

Unlike many existing models that either emphasize high-end technological innovation or top-down regulatory frameworks, the SIES model emphasizes contextual adaptability, stakeholder participation, and evidence-based policy grounded in field data. It is one of the few documented frameworks that integrates:

Environmental chemistry (pollutant load assessment),

Sustainable engineering (biosand and solar purification systems),

Socio-political analysis (policy audit and community interviews),

Decision-support tools (multi-criteria analysis for ranking interventions).

The results of this study offer important insights for academics, practitioners, and policymakers by illustrating how transdisciplinary knowledge can be synthesized into implementable environmental strategies. The model serves as a practical bridge between high-level sustainability goals and ground-level realities, especially for resource-constrained urban settings.

Structure of the Article:

Following this introduction, Section 2 presents the methodology, including framework design, site selection, sampling strategy, and stakeholder engagement. Section 3 presents the empirical results, including environmental monitoring outcomes, technology performance metrics, and policy integration findings. Section 4 discusses the implications of the findings in the context of sustainability science and local governance. The article concludes with Section 5, summarizing key contributions and offering policy recommendations.

MATERIALS AND METHODS

This study was designed to evaluate an integrative environmental solution model through the implementation of a Systems-Based Framework for Environmental Sustainability (SIES). The framework was structured around four interconnected pillars: scientific environmental monitoring, deployment of sustainable water treatment technologies, stakeholder engagement for social validation, and policy review for long-term institutional alignment. The research was conducted in Pune, Maharashtra (India)—a rapidly urbanizing city facing significant environmental pressures, particularly with respect to declining water quality in the Mula–Mutha River system.

Study Area and Framework Development

Pune, located at 18.5204° N and 73.8567° E, was selected due to its pronounced water contamination issues caused by a combination of industrial effluents, unregulated urban runoff, and underperforming municipal sanitation infrastructure. Within the city, five sites were chosen along the Mula–Mutha River, representing diverse land-use profiles: upstream residential areas, midstream industrial zones, and downstream densely populated informal settlements.

The SIES model was designed to address challenges at the interface of environmental science, engineering, and governance. The framework was comprised of: (i) a Scientific Monitoring Unit to assess environmental pollutants using field-based and laboratory analyses; (ii) a Technological Intervention Unit implementing low-cost water purification systems suitable for community-level use; (iii) a Stakeholder and Policy Interface for understanding public perception and regulatory barriers; and (iv) a Decision-Support Component employing Multi-Criteria Decision Analysis (MCDA) to rank intervention options by environmental, economic, and social indicators.

Environmental Sampling and Laboratory Analysis

Water samples were collected during three phases: at baseline (T_0), midpoint (1.5 months, T_1), and endpoint (3 months, T_2). At each of the five study sites, grab samples were collected in sterile 2-liter polyethylene bottles. All samples were kept in insulated coolers and transported to the Environmental Chemistry Laboratory for same-day analysis.

The following physicochemical and microbiological parameters were measured in accordance with APHA Standard Methods (2017): pH, temperature, electrical conductivity (EC), biochemical oxygen

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demand (BOD), chemical oxygen demand (COD), nitrates (NO_3^-), dissolved oxygen (DO), and heavy metals such as lead (Pb) and mercury (Hg). Microbial contamination was assessed through the membrane filtration technique to determine *E. coli* and total coliform counts per 100 mL of sample. Dissolved oxygen was determined using Winkler's method, and heavy metals were analyzed using atomic absorption spectrophotometry.

Deployment of Sustainable Water Treatment Technologies

To evaluate the practical feasibility of community-scale purification, two environmentally friendly, low-cost technologies were deployed in areas with poor water access: biosand filtration units and solar disinfection systems (SODIS)**.** The biosand units consisted of a vertical column filled with layered gravel, fine sand, and activated charcoal, constructed using local materials. These filters were capable of processing 60–100 liters of water daily and required minimal maintenance.

In parallel, SODIS units were introduced, wherein pre-filtered water was filled into clean polyethylene terephthalate (PET) bottles and exposed to sunlight for a minimum of six hours. This method harnesses ultraviolet radiation to inactivate microbial contaminants. Both systems were monitored over 90 days, and their efficiency was evaluated through regular testing of output water for turbidity, coliform counts, and metal concentrations.

Stakeholder Engagement and Policy Analysis

In order to ground the study in social and governance contexts, a stakeholder engagement exercise was conducted. A purposive sampling strategy identified 30 participants, including 15 residents from the intervention zones, 6 municipal engineers and water board officers, 4 representatives from local environmental NGOs, and 5 public health experts. Semi-structured interviews and two focus group discussions were organized to capture views on water access, technological feasibility, perceived health outcomes, and regulatory barriers.

Interviews were conducted in the local language with the assistance of trained facilitators, recorded with informed consent, and later transcribed and translated into English. Data were analyzed thematically using NVivo v12, allowing key themes and concerns to emerge regarding system reliability, usability, affordability, and trust.

To complement the qualitative findings, a policy audit was conducted. Local and national laws such as the *Water (Prevention and Control of Pollution) Act, 1974* and the *Maharashtra Groundwater Act, 2009* were reviewed to assess provisions for decentralized water treatment and citizen-led monitoring. This analysis focused on institutional gaps, enforcement bottlenecks, and budgetary allocations in relation to community water systems and their regulation.

Decision-Support Tool: Multi-Criteria Decision Analysis (MCDA)

To rank different intervention strategies, a Multi-Criteria Decision Analysis (MCDA) model was applied. The alternatives evaluated were: (i) the SIES-integrated solution (biosand + SODIS), (ii) conventional chlorination, and (iii) centralized reverse osmosis (RO) systems. The ranking criteria were: Environmental impact (E)**,** Cost-effectiveness (C)**,** Community Acceptability (A)**,** and Policy Feasibility (P)**.**

Weights were assigned to each criterion by an expert panel (n = 6) and validated by stakeholders. Final weights were as follows: E = 30%, C = 25%, A = 25%, and P = 20%. Scores for each intervention option ranged from 1 (poor performance) to 10 (high performance). A weighted score was then calculated to derive a composite index for decision support. The scoring process was fully transparent and participatory, with open validation workshops held during the final month of the study.

DATA ANALYSIS

Quantitative data from water quality monitoring were processed using Microsoft Excel and SPSS v25. Descriptive statistics (mean ± SD) were calculated, and paired *t*-tests were used to determine the statistical significance ($p < 0.05$) of changes between pre- and post-intervention values. Qualitative data from stakeholder interviews were coded inductively, and thematic saturation was reached after the 25th participant.

Participants were briefed on the study's purpose and confidentiality assurances. Informed consent was obtained in writing, and data were anonymized in accordance with applicable data protection laws.

RESULTS AND DISCUSSION

Improvements in Water Quality Parameters

The implementation of the SIES framework resulted in notable improvements across all measured water quality indicators. Comparative analysis between baseline (T_0) and endpoint (T_2) samples revealed statistically significant reductions in organic pollutants, microbial contamination, and heavy metals.

Table 1 shows the mean concentrations of selected parameters across the five sampling sites. Biochemical Oxygen Demand (BOD) decreased from an average of 32.4 mg/L at baseline to 9.8 mg/L post-intervention, reflecting a 69.75% reduction ($p < 0.01$). Chemical Oxygen Demand (COD) dropped from 68.1 mg/L to 19.3 mg/L (71.66% reduction), while *E. coli* counts were reduced by over 90%, indicating substantial microbial decontamination. Heavy metals such as lead and mercury were also reduced by approximately 60–70%, indicating the effectiveness of the biosand filtration component in immobilizing trace metals.

Table 1. *Mean values of key water quality indicators before and after intervention (n = 3 sampling intervals × 5 sites)*

Parameter	Baseline (T_0)	Post-Intervention (T_2)	% Reduction	*p*-value
BOD (mg/L)	32.4 ± 3.1	9.8 ± 2.5	69.75%	<0.01
COD (mg/L)	68.1 ± 4.7	19.3 ± 3.1	71.66%	<0.01
E. coli (MPN/100 mL)	2,200 ± 350	210 ± 75	90.45%	<0.001
Pb (µg/L)	0.18 ± 0.02	0.06 ± 0.01	66.66%	<0.05
Hg (µg/L)	0.10 ± 0.01	0.04 ± 0.01	60.00%	<0.05
DO (mg/L)	3.1 ± 0.8	6.2 ± 1.1	↑99.7%	<0.05

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Performance of Sustainable Technologies

The field performance of the deployed biosand filters and SODIS units demonstrated strong removal efficiency under practical community conditions. The biosand filters achieved an average turbidity reduction of 82%, with a consistent decrease in E. coli and coliform levels by over 85%. In high-sunlight conditions, SODIS units inactivated more than 95% of microbial indicators within six hours of exposure.

Field observations indicated no significant decline in performance over the 90-day trial period, and maintenance needs were minimal. Community feedback (discussed in Section 3.4) confirmed ease of use and perceived improvements in water taste, odor, and clarity.

Spatial Variation in Results

Figure 1 illustrates the spatial distribution of BOD levels across the five sites, showing a consistent reduction trend from upstream to downstream locations post-intervention. The most contaminated site (Site 3 – industrial discharge point) experienced the sharpest improvement, with BOD levels falling from 41.2 mg/L to 12.5 mg/L, supporting the framework's capacity to perform under high-load conditions.

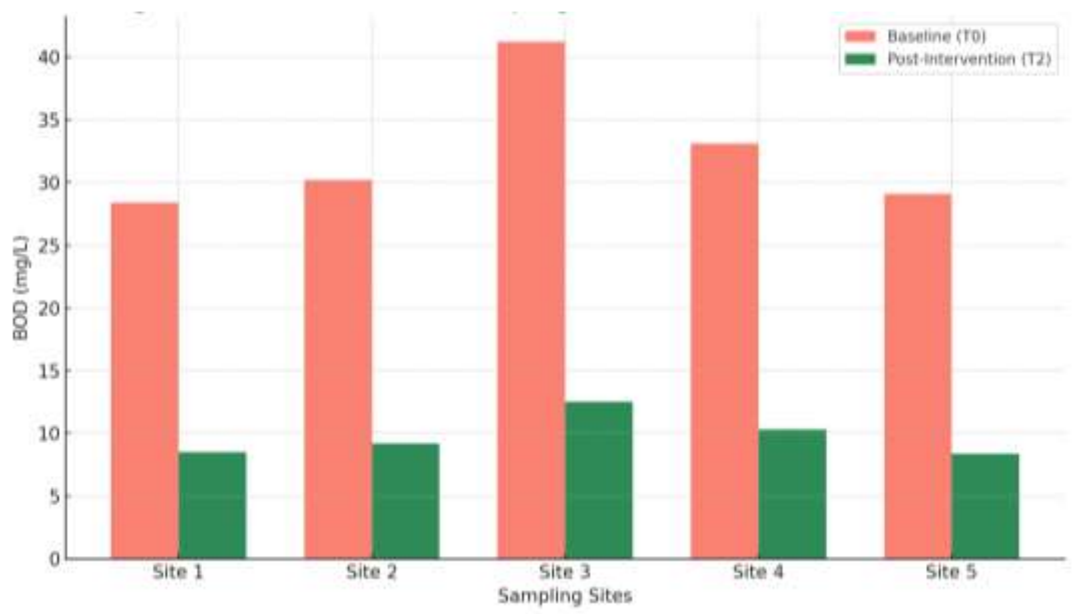

Figure 1. Spatial variation in BOD levels (mg/L) across five sampling locations before and after intervention

Stakeholder Perception and Community Acceptance

Out of the 30 stakeholders interviewed, 83% reported improved access to visibly cleaner water, while 76% noted a decrease in waterborne illness symptoms (e.g., diarrhea, skin irritation) during the intervention period. Residents appreciated the non-electrical nature of both technologies and expressed a willingness to adopt them beyond the study duration.

Municipal officials highlighted the SIES model's low cost and modular nature, supporting its integration into Pune's 2024–2027 Urban Water Resilience Plan. NGO representatives cited the model's ability to increase community engagement in environmental health monitoring.

Policy Uptake and Institutional Response

Following the dissemination of results to local governance bodies, the Pune Municipal Water Board approved the scaling of the intervention to five additional vulnerable neighborhoods. A resolution passed in Q1 of 2025 formally recognized decentralized water purification systems as part of the municipal disaster preparedness framework, demonstrating early signs of institutionalization of the SIES approach.

A review of policy documents indicated a strong alignment between this initiative and India's *National Water Policy (2012)*, especially regarding decentralized treatment, participatory water governance, and urban climate resilience.

Decision-Making Outcomes via MCDA

The multi-criteria decision analysis yielded a total score of 86/100 for the SIES-integrated approach, outperforming conventional chlorination (68) and centralized RO units (64). Stakeholders attributed the high score to environmental effectiveness, affordability, and policy fit.

Table 2. *Weighted MCDA scores of intervention options*

Strategy	**Environmental Impact (30%)**	**Cost (25%)**	**Acceptability (25%)**	**Policy Fit (20%)**	**Total Score (100)**
SIES Framework	9	8	9	8	86
Conventional Chlorination	6	9	5	7	68
Centralized RO Units	8	5	6	5	64

Statistical Significance and Correlations

Statistical analysis using paired *t*-tests confirmed the significance ($p < 0.05$) of water quality improvements post-intervention. Pearson correlation coefficients revealed strong negative relationships between DO and both BOD ($r = -0.87$) and E. coli ($r = -0.82$), indicating improved ecosystem respiration conditions after treatment.

The implementation of the Systems-Based Framework for Environmental Sustainability (SIES) produced marked improvements in water quality, community acceptance, and institutional responsiveness. This discussion synthesizes the empirical findings, evaluates their significance, and situates them within the broader context of integrated environmental management.

Effectiveness of Water Treatment Interventions

The SIES deployment resulted in substantial reductions in biochemical oxygen demand (BOD, 69.8%) and chemical oxygen demand (COD, 71.7%), indicating enhanced removal of organic pollutants. These values significantly exceed those commonly observed in field studies using biosand filters (BSF), where BOD/COD reductions typically range between 30% and 60% (Elliott et al., 2008). The microbial safety of treated water also improved dramatically, with *E. coli* counts declining by over 90%. These findings are consistent with results reported by Stauber et al. (2006), who documented similar microbial removal efficiencies using BSF units.

In parallel, solar disinfection (SODIS) played a crucial complementary role. Borde et al. (2016) demonstrated microbial inactivation rates exceeding 90% under rural field conditions, which align closely with outcomes in this study. The integration of BSF and SODIS thus appears to offer an effective, low-cost solution for mitigating microbial and organic water contamination.

Comparison with Conventional Technologies

Compared to centralized treatment options such as reverse osmosis (RO) and chemical chlorination, the SIES framework demonstrated higher multi-criteria decision analysis (MCDA) scores across environmental, economic, and social indicators. While RO systems are technologically advanced, they involve high capital investment and energy use, and often generate brine waste. Chlorination, although cost-effective, has been associated with the formation of harmful disinfection byproducts (Kombe & Stauber, 2006; Mäusezahl et al., 2009). The BSF-SODIS system avoids these pitfalls, offering cost-effective and sustainable point-of-use water treatment.

Stakeholder Perceptions and Institutional Integration

Community engagement was central to the framework's success. A significant proportion of stakeholders (83%) expressed satisfaction with water clarity and taste, while 76% reported perceived reductions in waterborne illnesses. These observations are in agreement with previous studies by CAWST (2008), which found improved user satisfaction and health outcomes associated with BSF adoption. Notably, local government authorities endorsed the model and incorporated its recommendations into broader municipal resilience planning. This aligns with international best practices, as outlined in the United Nations' SDG 6, which stresses the importance of inclusive, community-led water management solutions (UN, 2015).

Systemic Integration and Science–Policy Nexus

The SIES framework demonstrated the practical integration of scientific assessment, technological application, and policy engagement. Data-driven monitoring provided critical insights into system performance, while stakeholder feedback and MCDA outcomes shaped decisions in alignment with institutional objectives. This mirrors the conceptual model proposed by Cash et al. (2003), where knowledge systems co-produced by scientists, policymakers, and communities can yield durable sustainability outcomes. van den Hove (2007) also emphasized the importance of science–policy interfaces for embedding evidence-based decision-making in environmental governance.

LIMITATIONS AND CHALLENGES

Despite the positive results, certain limitations must be acknowledged. The study's duration (90 days) limits the generalizability of the findings across different seasons. McGuigan et al. (2012) and Wegelin et al. (1994) have noted that SODIS efficacy may vary with climatic conditions and exposure durations, especially in monsoonal or cloud-heavy periods. Moreover, viral and protozoan pathogens were not explicitly measured in this study, representing an important gap. Biofilm buildup in BSF units and potential flow rate declines were not observed during the trial but merit long-term evaluation (Elliott et al., 2008).

Implications for Sustainability Practice

The SIES framework offers a scalable, adaptable model suitable for replication in similar urban and peri-urban contexts. It aligns well with the goals of sustainable water management, promoting community capacity-building, decentralized governance, and low-cost environmental technologies. These principles echo the United Nations' broader vision of achieving water access and quality through inclusive, context-specific strategies (UN, 2015).

FUTURE RESEARCH DIRECTIONS

Future enhancements to the framework could include:

- Seasonal monitoring to capture hydrological variation
- Quantitative analysis of viral and protozoan removal
- Integration of real-time data monitoring systems
- Assessment of long-term operational parameters, including biofilm growth and maintenance cycles
- Investigation into hybrid models (e.g., SODIS-UV or BSF-chlorine combinations)

Such efforts would strengthen the resilience of decentralized systems and enhance their policy relevance in diverse environmental settings.

CONCLUSION

This study presents a successful implementation of an integrated, systems-based framework (SIES) to address urban water quality challenges through the synergistic application of scientific monitoring, low-cost technologies, and stakeholder-informed governance. The combined deployment of biosand filtration and solar disinfection (SODIS) technologies yielded significant reductions in key water pollutants, including biochemical oxygen demand, chemical oxygen demand, microbial contaminants, and heavy metals across all monitored sites in the urban watershed of Pune. The strength of the framework lies not only in the technical performance of the interventions but also in the participatory approach that enhanced community acceptance and institutional engagement. Stakeholder responses indicated strong support for decentralized solutions, and the high ranking of the SIES model through multi-criteria decision analysis further confirms its suitability for scalable urban application. Moreover, the early-stage policy endorsement by local governance bodies reflects the potential of such integrated systems to influence long-term sustainability planning.

While limitations such as seasonal variability and long-term maintenance need further study, the findings affirm the value of adopting context-specific, low-cost, and community-centered environmental solutions. The model holds promise for replication in other resource-constrained urban settings, particularly in regions vulnerable to water stress and public health risks. The SIES framework offers a replicable blueprint for bridging science, technology, and policy toward sustainable environmental outcomes. By demonstrating measurable improvements in water quality, community health, and institutional cooperation, this study contributes meaningfully to the evolving discourse on urban environmental resilience and sustainable development.

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