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Climate Resilient Wastewater Solutions for the Textile Industry (2020–2025): A Systematic Review

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Abstract
The textile industry is a significant contributor to environmental degradation, primarily due to its intensive water consumption and the discharge of untreated dyeing and finishing effluents. Climate change exacerbates these challenges by intensifying water scarcity and disrupting freshwater availability, underscoring the urgent need for sustainable and climate-resilient wastewater management strategies. This systematic review, conducted in accordance with PRISMA 2020 guidelines, synthesizes findings from 42 peer-reviewed studies published between 2020 and early 2025. It explores technological innovations, community-based initiatives, and evolving regulatory frameworks aimed at enhancing resilience in textile wastewater treatment. Advanced solutions such as membrane bioreactors, photocatalysis, floating treatment wetlands, microalgae-based systems, and graphene oxide adsorption demonstrate high pollutant removal efficiency while supporting circular economy principles. Proposed community-led models such as *Ecosew* and *Water Scouts* designed for implementation in developing countries, exemplify the potential of participatory governance in fostering local ownership, environmental stewardship, and adaptive capacity. Key findings indicate that advanced technologies such as membrane bioreactors and TiO_2-based photocatalysis achieve pollutant removal efficiencies exceeding 90%. Additionally, 28 of the reviewed studies employed composite indicators to evaluate sustainability and resilience. The review concludes with strategic recommendations for multisectoral policy reform and stakeholder collaboration, offering a comprehensive framework for climate-resilient wastewater governance, particularly in the Global South.

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1.0 Introduction
The global textile industry, a cornerstone of manufacturing economies and global trade, is simultaneously one of the most resource-intensive and polluting industrial sectors. It is estimated that the textile and apparel sector consume approximately 93 billion cubic meters of water annually, contributing significantly to water pollution due to the discharge of untreated or poorly treated wastewater laden with toxic chemicals, synthetic dyes, microfibers, and heavy metals (Gomes et al., 2024). This environmental footprint is magnified in regions like South and Southeast Asia, where the rapid expansion of textile production often outpaces infrastructure development and regulatory enforcement. At the same time, climate change is introducing new layers of stress to the textile production ecosystem. Rising temperatures, unpredictable rainfall, water scarcity, and increased frequency of extreme weather events threaten not only raw

material supply chains but also the availability and quality of freshwater required for production and dyeing processes. In this context, effective textile wastewater management is no longer merely a compliance issue but a critical resilience strategy for both environmental protection and industrial continuity (Schallenberg & Souza, 2023).

Over the past decade, considerable progress has been made in advancing wastewater treatment technologies, including membrane bioreactors (MBRs), advanced oxidation processes, and adsorption methods using innovative materials like graphene oxide. Parallel to these technical innovations, there has been a growing recognition of the importance of stakeholder engagement, particularly the involvement of local communities, in shaping sustainable and context-specific wastewater solutions (Shee Weng, 2024). Moreover, circular economy principles are increasingly being integrated into wastewater reuse and resource recovery frameworks, aligning industrial practices with broader environmental goals. However, despite these developments, significant gaps remain in our understanding and implementation of resilience-based approaches to textile wastewater management. Most existing research emphasizes isolated technological solutions or regulatory compliance without adequately addressing the interconnected dimensions of resilience, such as adaptability to climate-induced stress, inclusivity of community participation, and flexibility in governance systems. Few studies provide a comprehensive synthesis that integrates technological, social, and regulatory innovations within a resilience framework. Additionally, evaluation methodologies often lack standardized metrics that can account for both short-term efficiency and long-term adaptability. This article addresses these critical gaps by providing a comprehensive review of recent advances in textile wastewater management, emphasizing resilience as the central analytical lens. Drawing on literature published between 2020 and early 2025, this study synthesizes evidence across multiple dimensions: technological innovations (e.g., microalgae systems, photocatalysis, and FTWs), regulatory adaptations (e.g., EU directives and South Asian enforcement mechanisms), and participatory models (e.g., Water Scouts and Ecosew). Furthermore, the article examines emerging evaluation frameworks based on composite indicators to assess sustainability and resilience in wastewater strategies (Sun et al., 2020).

The added value of this research lies in its interdisciplinary approach, which bridges environmental engineering, climate adaptation science, and governance theory. By consolidating fragmented research and highlighting integrated solutions, the article contributes to the growing body of knowledge on climate-resilient industrial practices. It also offers actionable insights for policymakers, industry leaders, and researchers seeking scalable and context-sensitive solutions in the face of escalating climate uncertainty. Ultimately, this review not only maps the current state of resilient wastewater innovations in the textile sector but also establishes a conceptual foundation for future research, especially in low- and middle-income countries where climate vulnerability and industrial pollution intersect most acutely. By embedding resilience into the heart of wastewater discourse, the article proposes a paradigm shift from reactive compliance to proactive sustainability in textile production.

2.0 Methodology

2.1 Systematic Review Framework

This study employed a systematic review methodology to explore recent advancements in textile wastewater management, with a focus on climate resilience, sustainability, and stakeholder engagement. The review adhered to the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure methodological transparency, reproducibility, and rigor. This framework provided a structured process for identifying, screening, and selecting relevant literature, enabling a comprehensive synthesis of current knowledge and practices in the field.

2.2 Search Strategy and Selection Process

A comprehensive literature search was conducted across five major academic databases: ScienceDirect, SpringerLink, MDPI, Wiley Online Library, and SSRN. A combination of keywords and Boolean operators was used, including: *"textile wastewater," "climate resilience," "sustainable treatment,"* and *"circular economy."* The search was limited to peer-reviewed articles published in English between January 2020 and March 2025. From an initial pool of 123 records, duplicates and non-English or non-peer-reviewed sources were removed, resulting in 98 unique records. These were screened based on titles and abstracts, leading to the exclusion of 56 articles that did not meet the inclusion criteria. The remaining 42 full-text articles were assessed for eligibility, of which 28 were selected for final synthesis based on their direct relevance to the research objectives.

2.3 Inclusion and Exclusion Criteria

To ensure the relevance and quality of the studies included in this review, a set of predefined inclusion and exclusion criteria was applied during the screening and eligibility phases. These criteria were designed to align with the study's focus on climate-resilient wastewater management within the textile industry. Only studies that directly contributed to the understanding of sustainable treatment technologies, governance models, or resilience frameworks were considered.

Articles were included if they:

- Focused on textile wastewater treatment technologies or governance
- Addressed climate resilience or sustainability dimensions
- Provided empirical data, case studies, or conceptual frameworks

Articles were excluded if they:

- Were not peer-reviewed
- Focused solely on non-textile industries
- Lacked relevance to climate adaptation or resilience

2.4 Data Analysis and Thematic Categorization

The selected studies were analyzed qualitatively and categorized into three thematic domains: technological innovations, regulatory frameworks, and social dimensions.

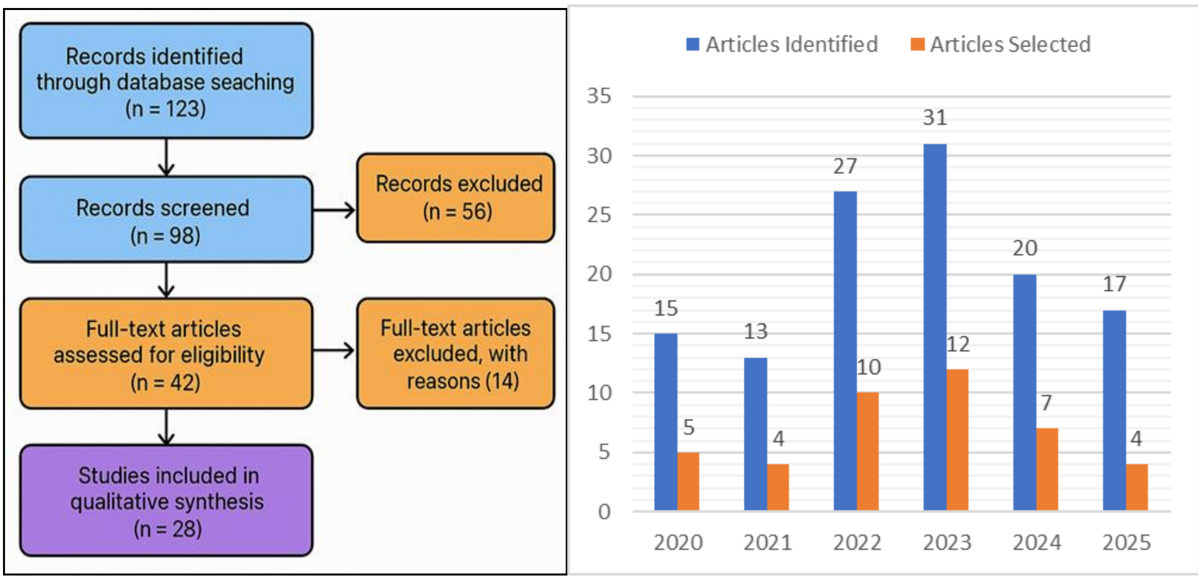

Figure 1 (A): PRSIMA Process Flow Diagram. **(B):** Year wise distribution of Paper Identified and Paper Selected for Review, source: author's compilation.

This thematic structure enabled a holistic assessment of how current research aligns with the principles of resilient and sustainable wastewater management. Notably, the review observed a surge in scholarly attention during 2022 and 2023, particularly in the development of advanced treatment technologies such as membrane bioreactors, microalgae-based systems, and graphene oxide-enhanced adsorption. The integration of participatory governance and climate adaptation strategies within these studies highlights a growing interdisciplinary approach to addressing the complex challenges of textile wastewater management. Figure 1A illustrates the PRISMA 2020 flow diagram used for the identification and selection of articles included in this review, while Figure 1B presents the year-wise distribution of articles identified and selected.

3.0 Technological Innovations and Sustainable Practices

Recent advancements in textile wastewater treatment technologies have significantly strengthened the sector's ability to address environmental challenges while promoting sustainability and circular economy principles. A growing body of research highlights the transformative potential of membrane bioreactors (MBRs), advanced oxidation processes (AOPs), and solar-powered photodegradation systems in achieving high pollutant removal efficiency and enabling resource recovery (Chen et al., 2023; Deshmukh et al., 2025). MBRs, which combine biological degradation with membrane filtration, are particularly effective in removing organic matter, dyes, and pathogens. Their compact design and low sludge generation make them ideal for retrofitting in space-constrained industrial zones (Deshmukh et al., 2025). These systems are increasingly preferred for their operational stability under variable climatic conditions an essential feature for climate-resilient infrastructure. Photocatalysis, particularly using titanium dioxide (TiO_2), has emerged as a solar-compatible, energy-efficient method for degrading complex dye molecules. Crovella and Paiano (2023) emphasize its ability to minimize secondary pollution and by-products, positioning it as a sustainable alternative to conventional chemical treatments. Solar-assisted photodegradation further enhances energy efficiency, especially in sun-rich regions such as South Asia. Floating Treatment Wetlands (FTWs) offer a decentralized, nature-based solution that utilizes aquatic plants (macrophytes) for pollutant uptake and ecological restoration. As noted by Wei et al. (2020), FTWs provide additional co-benefits such as biodiversity enhancement and carbon sequestration, making them particularly suitable for peri-urban and rural textile clusters lacking centralized infrastructure.

Microalgae-based bioremediation systems represent a dual-function innovation not only absorb nutrients and heavy metals from wastewater but also generate biomass that can be converted into biofuels, fertilizers, or animal feed (Nagarajan et al., 2022). This approach supports circular economy objectives by transforming waste into value-added products, while also contributing to carbon capture and enabling integration with other treatment technologies. Graphene oxide (GO) has attracted attention for its exceptional adsorption capacity for dyes and heavy metals. Velusamy et al. (2021) report that GO-based materials exhibit rapid uptake kinetics, high surface area, and reusability, making them cost-effective over multiple treatment cycles. Their nanostructured properties also allow for integration into hybrid systems with membranes or photocatalysts. A detailed comparison of these technologies, including their core functionalities and sustainability benefits, is presented in Table 1. Collectively, these innovations not only improve treatment efficiency but also reduce environmental footprints and operational costs. They exemplify the convergence of environmental stewardship and industrial profitability, reinforcing the textile sector's transition toward resilient and sustainable wastewater management. Crucially, their adaptability to climate-induced stressors such as fluctuating water quality and temperature extremes positions them as essential components of future-ready infrastructure.

Table 1: Technological Innovations in Textile Wastewater Management

Technology	Key Functionality	Sustainability Advantage	Source
Membrane Bioreactors (MBRs)	High-efficiency contaminant removal	Compact design, low sludge production	Deshmukh et al., 2025
Photocatalysis (TiO_2-based)	Degrades dyes under solar radiation	Utilizes renewable energy, low by-products	Crovella & Paiano, 2023
Floating Treatment Wetlands (FTWs)	Bioaccumulation via macrophytes	Low energy input, biodiversity enhancement	Wei et al., 2020
Microalgae Systems	Pollutant uptake, biomass generation	Circular economy, carbon capture	Nagarajan et al., 2022
Graphene Oxide Adsorption	Adsorbs dyes and heavy metals	Reusable, rapid uptake	Velusamy et al., 2021

Source: author's compilation from reviewed articles

3.1 Community Engagement and Participatory Governance

Participatory governance models are increasingly recognized as vital to the success of decentralized wastewater management, particularly in climate-vulnerable regions. Two notable examples discussed in the literature are *Water Scouts* and *Ecosew*. *Water Scouts* is a real, youth-led initiative implemented in India that focuses on local water monitoring, environmental education, and community awareness. It engages school-aged youth in tracking water quality and promoting conservation practices, thereby fostering early environmental stewardship and intergenerational knowledge transfer. In contrast, *Ecosew* is a conceptual framework proposed for Bangladesh, designed to integrate eco-friendly textile production with decentralized wastewater treatment. It envisions a community-based model that combines traditional knowledge, green skills training, and employment generation in rural textile clusters. By explicitly distinguishing between these models one operational and the other aspirational—the review highlights both the practical impact of existing initiatives and the innovative potential of emerging frameworks. Together, they underscore the importance of empowering local stakeholders, especially women and youth, in pollution tracking, awareness campaigns, and the maintenance of decentralized treatment systems.

Table 2: Key Drivers of Resilient Wastewater Management

Dimension	Strategy/Mechanism	Impact on Resilience	Source
Community Engagement	Participatory planning, local monitoring, education	Increases ownership, adaptive capacity	Shee Weng, 2024
Regulatory Innovation	Incentives, adaptive standards, cross-sector coordination	Bridges gaps in enforcement and policy integration	Obaideen et al., 2022
Evaluation Frameworks	Composite indicators, SAT models	Holistic performance measurement	Sun et al., 2020
Financial Mechanisms	PPPs, subsidies, climate funds	Facilitates technology adoption and capacity building	Tan et al., 2023
Health & Safety	Worker protection in technology deployment	Enhances social equity and sustainable development	Fiorilli, 2023

Source: author's compilation from reviewed articles

The integration of indigenous knowledge systems significantly enhances the cultural and ecological relevance of wastewater management strategies. Traditional practices such as water conservation techniques, plant-based filtration methods, and seasonal water use patterns can effectively complement scientific approaches, resulting in hybrid models that are both technically sound and socially accepted. These synergies foster greater community ownership and long-term sustainability. A detailed overview of the key drivers supporting resilient wastewater management is presented in Table 2. In addition, community-led initiatives that combine education, skill development, and employment generation offer multifaceted benefits. For example, training programs focused on wastewater monitoring or eco-friendly dyeing techniques not only build local technical capacity but also create green jobs. This socio-economic integration strengthens trust between communities and industries, reduces resistance to infrastructure projects, and supports the long-term viability of decentralized wastewater systems. Such participatory approaches also contribute to environmental justice, ensuring that marginalized groups have a voice in decisions affecting their water resources. As Wang et al. (2022) argue, inclusive governance fosters resilience by embedding adaptability and accountability into the very fabric of wastewater management.

3.3 Adaptive Regulatory Frameworks

While technological innovation in wastewater treatment has advanced rapidly, regulatory frameworks have often struggled to keep pace. Traditional regulations tend to focus narrowly on effluent discharge limits, overlooking broader concerns such as climate variability, cumulative ecological impacts, and lifecycle emissions. In the European Union, directives like REACH and the Water Framework Directive provide a robust legal foundation but suffer from inconsistent implementation across member states (Karl et al., 2019). Despite the existence of formal legal frameworks for wastewater management, countries like Bangladesh and India continue to struggle with effective enforcement. These challenges stem from fragmented institutional responsibilities, inadequate monitoring infrastructure, and limited regulatory oversight. As a result, even the most advanced treatment technologies fail to deliver their intended impact due to systemic regulatory inertia (Kallawar & Bhanvase, 2024). To address these gaps, scholars advocate for adaptive governance models that are flexible, data-driven, and responsive to emerging risks. Obaideen et al. (2022) propose the integration of compound indicator-based evaluation systems such as those developed by Sun et al. (2020) to assess not just compliance, but also resilience, sustainability, and social impact. These indicators can include metrics like energy efficiency, community satisfaction, and climate adaptability. Furthermore, adaptive frameworks should incentivize innovation through subsidies, tax breaks, or public-private partnerships (Tan et al., 2023). They must also promote inter-sectoral coordination, linking environmental agencies with urban planning, public health, and industrial development bodies. Such cross-cutting governance is essential for managing the complex, interconnected challenges posed by climate change and industrial pollution. Ultimately, a shift toward adaptive regulation can bridge the gap between technological potential and real-world implementation, ensuring that wastewater solutions are not only effective but also equitable and future-proof.

3.4 Metrics for Sustainability and Resilience

Evaluating the sustainability and resilience of textile wastewater treatment systems requires a multidimensional approach that goes beyond conventional performance metrics. Sun et al. (2020) propose a composite indicator framework that integrates technical, economic, environmental, and social dimensions. This approach enables a holistic assessment of treatment technologies, facilitating cross-context comparisons and informed decision-making.
Key indicators in this framework include:

- Pollutant Removal Efficiency: Measures the system's ability to eliminate dyes, heavy metals, and organic contaminants.
- Energy Consumption: Assesses the energy intensity of treatment processes, with a preference for low-carbon or renewable-powered systems.
- Operational and Capital Costs: Evaluates both upfront investment and long-term maintenance expenses.
- Social Acceptance: Captures community perceptions, willingness to adopt, and trust in the technology.

To operationalize these indicators, tools like the Sustainability Assessment of Technologies (SAT) framework are employed. SAT provides a structured methodology for evaluating technologies across life cycle impacts, economic feasibility, and social equity, making it particularly useful for policymakers and industry stakeholders navigating trade-offs between cost, efficiency, and inclusivity. A typical SAT framework for textile wastewater solutions is given below as Figure 2.

Figure 2: SAT Framework for Assessing Textile Wastewater Solutions, *Source: Adapted and expanded from Sun et al. (2020).*

The incorporation of community-derived indicators such as local perceptions of water quality, equity in access, and environmental justice adds critical legitimacy and accountability to the evaluation of wastewater treatment systems. These qualitative metrics ensure that the lived experiences and concerns of affected populations are reflected in performance assessments, particularly in regions where formal monitoring mechanisms are limited or absent. In parallel, resilience-specific indicators such as a system's adaptability to climate extremes, redundancy in treatment capacity, and recovery time following disruptions are increasingly being integrated into evaluation frameworks. These metrics are essential for assessing how well a system can withstand and recover from shocks such as floods, droughts, or industrial accidents. By combining both quantitative and qualitative indicators, composite evaluation frameworks offer a dynamic and inclusive approach to assessing wastewater solutions. They facilitate a shift from traditional compliance-based models to resilience-oriented governance, ensuring that technologies are not only effective under optimal conditions but also robust in the face of uncertainty. A synthesized matrix encompassing these dimensions is presented in Table 3.

Table 3: A Synthesized Matrix for Resilient Wastewater Solutions in the Textile Industry

Component	Example/Model	Functionality	Sustainability/Resilience Advantage	Key References
Technology	Membrane Bioreactors (MBRs)	High-efficiency contaminant removal	Compact design, low sludge, adaptable to climate stress	Deshmukh et al., 2025
	TiO_2 Photocatalysis	Solar-assisted dye degradation	Renewable energy use, minimal by-products	Crovella & Paiano, 2023
	Floating Treatment Wetlands (FTWs)	Phytoremediation via macrophytes	Low energy input, biodiversity restoration	Wei et al., 2020
	Microalgae Systems	Pollutant uptake and biomass generation	Circular economy, carbon capture	Nagarajan et al., 2022

	Graphene Oxide Adsorption	Adsorption of dyes and heavy metals	High efficiency, reusability	Velusamy et al., 2021
Community Engagement	Water Scouts (India)	• Local water monitoring • Youth education • Awareness campaigns	Build trust, enhance adaptive capacity	Shee Weng, 2024
	Ecosew (Bangladesh)	• Co-creation of solutions • Skill development • Indigenous knowledge use	Job creation, indigenous knowledge integration	Shee Weng, 2024
Regulatory Frameworks	REACH & Water Framework Directive (EU)	Chemical safety and water quality standards	Precedent-setting, but inconsistently enforced	Karl et al., 2019
	South Asian Legal Frameworks	Effluent discharge regulation	Existing laws, weak enforcement	(Kallawar & Bhanvase, 2024).
	Adaptive Governance Models	• Innovation incentives • Cross-sector coordination • Composite indicators	Bridges innovation-policy gap, supports resilience	Obaideen et al., 2022
Evaluation Metrics	Composite Indicators	Multidimensional performance assessment	Integrates technical, economic, social, and resilience dimensions	Sun et al., 2020
	SAT Framework	Life cycle and sustainability assessment	Supports decision-making across contexts	Sun et al., 2020
Resilience Focus	Decentralized Infrastructure	Localized treatment systems	Climate adaptability, redundancy, faster recovery	Schallenberg & Souza, 2023

Source: author's compilation from reviewed articles

4.0 Critical Analysis of Resilient Wastewater Solutions

A comprehensive evaluation of resilient wastewater strategies in the textile industry reveals a dynamic interplay between technological innovation, social engagement, regulatory evolution, and evaluation methodologies. While significant progress has been made, several systemic challenges persist that limit the scalability and effectiveness of these solutions, particularly in climate-vulnerable regions.

4.1 Technological Dimension

Advanced treatment technologies such as membrane bioreactors (MBRs), TiO_2-based photocatalysis, floating treatment wetlands (FTWs), microalgae systems, and graphene oxide adsorption demonstrate high pollutant removal efficiency and alignment with circular economy principles (Deshmukh et al., 2025; Crovella & Paiano, 2023; Wei et al., 2020; Nagarajan et al., 2022; Velusamy et al., 2021). These systems offer operational stability under climate-induced stressors and enable resource recovery. However, their deployment is often hindered by high capital costs, energy demands, and the need for skilled operation and maintenance. In low-resource settings, these barriers can limit adoption, underscoring the need for modular, decentralized, and cost-effective alternatives.

4.2 Social and Community Engagement

Community-led models such as India's "Water Scouts" and Bangladesh's "Ecosew" illustrate the transformative potential of participatory governance in wastewater management (Shee Weng, 2024). These initiatives enhance local ownership, environmental literacy, and decentralized monitoring, while also integrating indigenous knowledge and creating green jobs. However, their implementation often faces real-world challenges. In some industrial zones, local textile manufacturers have shown resistance to community oversight, perceiving it as a threat to operational autonomy or fearing increased regulatory scrutiny (Wang et al., 2022). Additionally, sustaining long-term engagement can be difficult due to community fatigue especially when volunteers encounter limited institutional support, lack of feedback mechanisms, or unclear pathways for impact. For instance, several Water Scouts chapters reported declining participation after initial enthusiasm, citing resource constraints and repetitive tasks without tangible outcomes. Ecosew, while conceptually promising, has yet to overcome barriers related to funding continuity and integration with formal governance structures. These challenges underscore the need for inclusive frameworks that embed environmental justice, provide sustained capacity-building, and foster trust between communities and industries to ensure the scalability and resilience of such models.

4.3 Regulatory and Institutional Frameworks

Regulatory systems in many textile-producing countries remain reactive and fragmented. While frameworks like the EU's REACH and Water Framework Directive offer robust precedents, their inconsistent enforcement limits effectiveness (Karl et al., 2019). In South Asia, legal mandates for effluent treatment often lack the institutional capacity and inter-agency coordination needed for implementation (Kallawar & Bhanvase, 2024). Adaptive governance models featuring dynamic standards, cross-sector collaboration, and innovation incentives are emerging but remain underutilized. Bridging the gap between policy and practice requires not only legal reform but also the integration of climate resilience into regulatory design.

4.5 Evaluation of Metrics and Resilience Indicators

Traditional performance metrics focused on pollutant removal and cost fail to capture the multidimensional nature of resilience. Composite indicator frameworks and tools like the Sustainability Assessment of Technologies (SAT) offer a more holistic lens by incorporating technical, economic, environmental, and social dimensions (Sun et al., 2020). However, resilience-specific indicators such as system adaptability to climate extremes, redundancy, and recovery time are still underdeveloped and inconsistently applied. The inclusion of community-derived indicators (e.g., perceived water quality, access equity) can enhance legitimacy and contextual relevance, especially in regions with limited formal monitoring infrastructure. A critical analysis of proposed solutions is given below in table 4 with their strengths and limitations.

Table 4: Critical Analysis of Resilient Wastewater Solutions

Dimension	Key Findings	Strengths	Limitations	Opportunities for Integration or Scaling
Technological	MBRs, TiO_2 photocatalysis, FTWs, microalgae, and GO show high efficiency and circular economy alignment.	High pollutant removal, climate adaptability, resource recovery.	High cost, infrastructure demands, limited scalability in low-resource settings.	Modular deployment, hybrid systems, public-private partnerships for infrastructure investment.
Social	Participatory models (e.g., Water Scouts, Ecosew) enhance monitoring, education, and local ownership.	Builds trust, creates jobs, integrates indigenous knowledge.	Requires long-term support, uneven inclusion of marginalized groups.	NGO partnerships, school-based programs, integration with local governance structures.
Regulatory	Existing frameworks are often outdated or poorly enforced; adaptive models emerging.	Some progress in compound indicators and innovation incentives.	Weak enforcement, fragmented governance, lack of climate integration.	Policy labs, adaptive licensing, regional cooperation platforms.
Evaluation	Composite indicators and SAT frameworks enable multidimensional assessment.	Integrates technical, economic, and social metrics.	Resilience indicators are still evolving; limited use of community-based metrics.	Open-source indicator platforms, community-led monitoring, integration into ESG reporting

Source: author's compilation from reviewed articles

5.0 Limitations

This review is subject to several limitations. First, the literature search was limited to English-language publications, which may have excluded relevant studies in other languages. Second, the review focused on peer-reviewed journal articles, potentially overlooking valuable insights from grey literature, industry reports, and policy documents. Third, while the study aimed to synthesize findings across diverse geographies, the majority of included studies were concentrated in South and Southeast Asia, limiting the generalizability of findings. Finally, the evaluation of technologies and governance models was based on reported outcomes rather than field validation, which may affect the accuracy of performance assessments.

6.0 Conclusion

This review underscores the urgent need for a paradigm shift in textile wastewater management, particularly in the face of escalating climate stress and environmental degradation. The integration of advanced treatment technologies such as membrane bioreactors, solar-assisted photocatalysis, floating wetlands, microalgae systems, and graphene oxide adsorption demonstrates significant potential for enhancing pollutant removal, resource recovery, and operational resilience. However, their effectiveness is contingent upon localized adaptation, financial feasibility, and institutional support, especially in low- and middle-income countries. Equally critical is the role of community engagement and participatory governance. Initiatives like Water Scouts in India and Ecosew in Bangladesh illustrate how grassroots involvement can foster environmental stewardship, improve monitoring, and ensure the social legitimacy of wastewater interventions. These models highlight the importance of integrating indigenous knowledge, education, and employment generation into environmental strategies. The review also reveals that regulatory frameworks must evolve from static compliance models to adaptive governance systems that are responsive to climate variability and socio-ecological complexity. The adoption of composite indicators and tools like the Sustainability Assessment of Technologies (SAT) framework offers a promising path toward holistic evaluation, enabling decision-makers to balance technical performance with economic, social, and environmental considerations.

Looking ahead, a clear research agenda is essential to guide future efforts. This should include longitudinal studies to assess the long-term effectiveness and resilience of wastewater technologies, policy piloting to test adaptive governance models in diverse contexts, and exploration of technology diffusion pathways to accelerate adoption in low-resource settings. Investment in capacity building, cross-sector coordination, and dynamic policy instruments will be vital to operationalize these strategies. By aligning technological advancement with inclusive governance and robust evaluation, the textile sector can transition from being a major polluter to a global leader in sustainable and climate-resilient industrial transformation.

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