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Nature-based solutions for climate-resilient industrial wastewater management: A framework and semi-systematic synthesis

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ABSTRACT

Industrial effluent treatment plants are still designed mainly for average flow, average load, reliable power, and stable rainfall. These assumptions are weakening in climate-exposed industrial regions. Heatwaves, intense rainfall, flooding, drought, salinity intrusion, and power disruption now disturb the hydraulic and biological conditions on which treatment depends. This review reframes nature-based solutions (NBS) for industrial wastewater as engineered ecological infrastructure for disturbed conditions, not as decorative green features or substitutes for essential treatment. It develops the Climate-Resilient Engineered Ecological Infrastructure (CREEI) framework, linking an external climate-stressor regime, an industrial wastewater system understood as a social-ecological-technological system, and an internal resilience cycle of resistance, absorption, recovery, and adaptation. A semi-systematic review of 55 peer-reviewed sources and five additional methodological sources is used to appraise six NBS options against six resilience functions. The synthesis shows that no single option is sufficient. Resilience comes from treatment trains that combine hydraulic reserve, conventional pretreatment, ecological polishing, adsorptive media, reuse storage, and catchment buffers. Recent evidence on compound extremes, microbial decline, clogging, drought-rewetting pulses, and sink-to-source reversal also shows why stable-condition removal efficiency can create an adaptation illusion. The article proposes a nested design and governance model for factory, industrial-park, and catchment scales. It is especially relevant for monsoonal deltaic industrial economies such as Bangladesh, where textile production pressure, weak drainage, land scarcity, water stress, and flood exposure coincide.

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INTRODUCTION

Industrial wastewater management is still treated mostly as a factory-bound technical task. Pumps, tanks, aerators, chemicals, sludge lines, and laboratory tests are kept inside the fence. This is necessary, but it is no longer enough in flood-prone and water-stressed industrial regions.

Rainfall, drainage congestion, heat, freshwater scarcity, salinity, and grid instability now enter the treatment process from outside the factory boundary and disturb hydraulic retention, dissolved oxygen, microbial activity, sludge control, and final discharge quality (Wang *et al.*, 2023; Wu *et al.*, 2015).

Industrial effluent is also diverse. Textile and dyeing wastewater contains colour, salts, surfactants, auxiliaries, suspended solids, and variable pH. Tannery wastewater adds chromium, sulphide, salinity, and high organic load. Dairy, brewery, and food-processing effluents are more biodegradable but nutrient-rich and sensitive to shock loading. Refinery, petrochemical, pulp-and-paper, landfill leachate, and mixed streams contain hydrocarbons, phenols, fibres, colour, high-strength organics, and recalcitrant compounds (Yalcuk and Ugurlu, 2009; Yaseen and Scholz, 2019; Vymazal, 2014). Therefore, climate resilience cannot be delivered by one generic green unit. It requires source control, sector-specific treatment logic, and a clear understanding of how ecological and engineered units behave under disturbance.

NBS offer a practical route to strengthen industrial wastewater systems when they are engineered with discipline. In wastewater practice they include constructed wetlands, floating treatment wetlands, high-rate algal ponds, vegetated filters, riparian buffers, storage and reuse ponds, biochar-amended beds, and hybrid ecological treatment trains. Constructed wetlands have moved beyond domestic wastewater and are now used for industrial polishing, reclamation, and resource-oriented treatment (Sowińska-Świerkosz and García, 2022; Vymazal, 2010; Masi *et al.*, 2018; Wang *et al.*, 2023). Their design has also developed through work on plants, substrates, hydraulic loading, microbial mechanisms, and long-term operation (Akratos and Tsihrintzis, 2007; Brisson and Chazarenc, 2009; Dordio and Carvalho, 2013; Faulwetter *et al.*, 2009; Vymazal, 2011, 2013).

The problem is that much of the evidence still reports removal percentages under ordinary conditions. BOD, COD, suspended solids, nutrients, colour, metals, and selected contaminants are important, but they do not show whether a system can resist flood pulses, absorb shock loads, recover after drought, or adapt to rising salinity. Recent work warns that NBS validated under moderate conditions may fail nonlinearly under compound extremes, creating an adaptation illusion: the belief that a green investment has secured resilience when it may fail at the exact moment receiving water is most exposed (Alamdari, 2026).

This article addresses that gap by treating NBS as climate-resilient engineered ecological infrastructure. Its contribution is fourfold. First, it develops the CREEI framework. Second, it converts scattered evidence into a resilience appraisal of six NBS options. Third, it proposes a multi-scale design and governance model across factory, industrial-park, and catchment scales.

Fourth, it applies the argument to Bangladesh and similar monsoonal textile economies, where climate stress, drainage weakness, industrial growth, and buyer pressure meet in one setting.

CONCEPTUAL AND THEORETICAL FRAMEWORK

From treatment efficiency to resilience

Resilience theory matters because industrial wastewater systems are no longer operating under stationary conditions. Engineering resilience focuses on return to performance after disturbance.

Ecological resilience highlights how much disturbance a system can absorb before shifting into another state (Holling, 1973). Infrastructure resilience adds capacities such as robustness, redundancy, resourcefulness, and rapidity (Bruneau *et al.*, 2003). Resilience engineering further emphasises the ability to resist, absorb, recover, and adapt when systems face surprise and constraint (Woods, 2015).

In this article, industrial wastewater resilience means the capacity to continue protecting receiving water across disturbed conditions. Resistance prevents immediate failure. Absorption takes a short shock without collapse. Recovery restores stable function after stress. Adaptation changes design, operation, and governance as climate conditions shift. Ecological units can support all four functions, but only when their limits are known and managed (Hassan *et al.*, 2021; Masoud *et al.*, 2022).

The wastewater system as a social-ecological-technological system

A treatment train succeeds or fails through more than technology. It contains ecological components such as macrophytes, root zones, microbes, sediments, substrates, and carbon pools.

It also contains social components such as operators, cost-sharing rules, regulators, buyers, surrounding communities, and park governance. A flood pulse can stress pumps and tanks, disturb plants and microbes, and expose weak accountability at the same time. This is why a social-ecological-technological systems lens is useful for NBS planning (Ilyas and Masih, 2017; Wu *et al.*, 2015).

The same logic supports a safe-to-fail approach. Industrial wastewater systems should not assume perfect protection. They should degrade in controlled ways when thresholds are crossed.

Emergency storage, modular cells, gravity-fed polishing, protected electrical systems, and overflow routing can prevent treatment failure from becoming direct pollution (Ahern, 2011).

Engineered ecological infrastructure and CREEI

The CREEI framework brings the resilience argument into the design of industrial wastewater systems. It views nature-based solutions not as passive green additions, but as engineered ecological infrastructure that must work under stress. The framework has three connected layers.

The first layer is the external climate-stressor regime, including rainfall extremes, flooding, heat, drought, salinity, and power disruption. The second layer is the industrial wastewater system, which includes technical units, ecological components, operators, institutions, and surrounding communities. The third layer is the resilience-response cycle, where the system must resist disturbance, absorb short-term shocks, recover after disruption, and adapt as climate pressure changes over time.

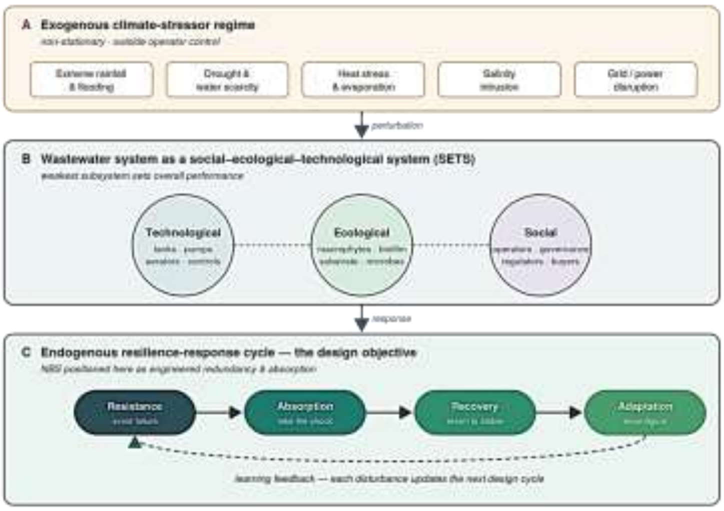

Fig. 1. The climate-resilient engineered ecological infrastructure (CREEI) framework, linking climate stressors, social-ecological-technological subsystems, and resilience responses

Fig. 1 presents this logic by linking climate stressors, social-ecological-technological subsystems, and resilience responses in one framework. The main message is that ecological treatment units cannot be treated as self-managing systems. They need hydraulic control, pollutant-specific design, routine monitoring, maintenance budgets, trained operators, and clear institutional responsibility. Without these conditions, NBS may add landscape value but may not provide reliable wastewater resilience under disturbed climate conditions.

REVIEW METHODOLOGY

This article uses a semi-systematic interpretive review. A full meta-analysis was not suitable because industrial wastewater studies vary widely in wastewater source, pollutant strength, hydraulic loading, climate condition, substrate type, vegetation, pretreatment, monitoring period, and performance indicators. The review therefore focused on identifying patterns, mechanisms, design lessons, and resilience implications across a diverse evidence base rather than producing a pooled statistical estimate.

The evidence was collected from peer-reviewed literature published between 2001 and 2026.

The main databases were Scopus, Web of Science, and ScienceDirect. Reference chaining was also used to include foundational reviews and relevant recent studies. Search terms combined ecological treatment concepts with industrial wastewater, sector-specific terms, and climate-resilience terms such as flood, drought, salinity, heat, reuse, and system resilience.

Titles and abstracts were screened for relevance to ecological treatment of industrial effluent, treatment mechanisms, design, operation, reuse, or climate performance. Studies dealing only with domestic wastewater were excluded unless they provided transferable mechanisms for industrial application. Non-peer-reviewed items and opinion-based papers were also excluded.

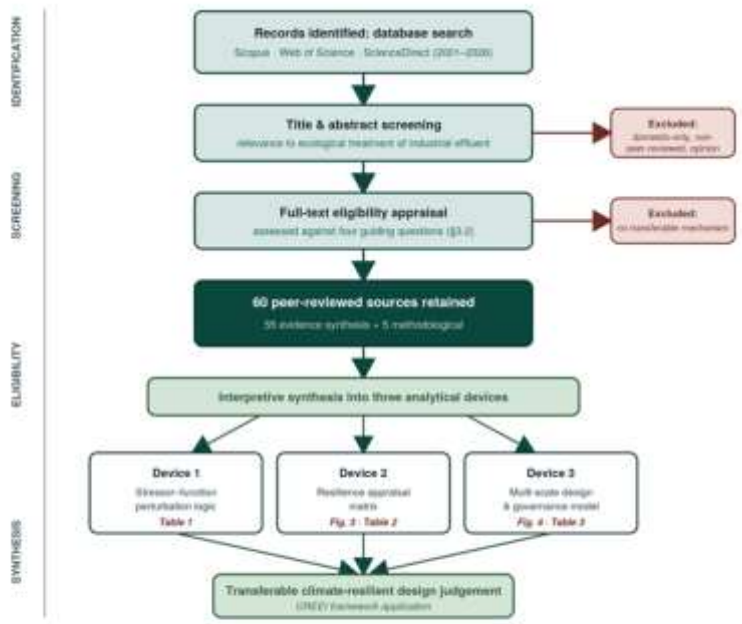

Fig. 2. Semi-systematic evidence selection and synthesis protocol

Fifty sources formed the main review base, while five additional sources were used to strengthen the treatment of operating envelopes, compound climate extremes, and resilience assessment.

Fig. 2 summarises the evidence selection and synthesis protocol used in the review. The review was guided by four questions: which climate stresses reshape industrial wastewater quantity and quality, which NBS options match different pollutant profiles, how these options can support resistance, absorption, recovery, and adaptation, and what design or governance barriers limit their use in monsoonal deltaic economies. The analysis produced three outputs: a stressor-function logic, a resilience appraisal matrix, and a multi-scale design and governance model.

CLIMATE STRESS AND INDUSTRIAL WASTEWATER RISK

Climate stress changes both the volume and the quality of industrial wastewater. Extreme rainfall increases unwanted inflow, reduces hydraulic retention time, and can force bypass if the system has limited reserve capacity. Floodwater can damage pumps, electrical panels, chemical stores, sludge-handling areas, and sampling points. Drought works differently. It reduces dilution and can increase COD, salts, colour, nutrients, and toxicity, especially when industries reduce washing water or apply internal reuse without adequate quality control. Heatwaves lower dissolved oxygen, increase evaporation, raise odour risk, and can destabilise microbial communities. Salinity intrusion adds another pressure by stressing freshwater plants and inhibiting biological treatment processes (Calheiros *et al.*, 2007; Rai, 2009).

These impacts are not always linear. A dry period followed by intense rainfall can mobilise nutrients, sediments, and pollutants that accumulated during low-flow conditions. In some cases, a desiccated wetland or ecological polishing unit may briefly shift from pollutant sink to pollutant source after rewetting. Heat and desiccation can also weaken the microbial communities responsible for nitrification, denitrification, and organic matter removal (Alamdari, 2026). Long-term clogging and media exhaustion create further risk, particularly where operation and maintenance are weak (Nivala *et al.*, 2012; Vymazal, 2018).

Table 1. Climate-stress pathways and implications for industrial wastewater treatment

Climate stressor	Immediate effect on wastewater	Treatment risk	Nature-based resilience response	Key design caution
Extreme rainfall and flooding	High hydraulic load, dilution, inflow and infiltration	Short retention, washout, bypass	Equalisation, freeboard, modular cells, overflow storage	Prevent untreated flood bypass into ecological cells
Drought and scarcity	Lower dilution, higher concentration	Toxic shock, high COD, salinity, colour, nutrients	Reuse ponds, polishing wetlands, algal recovery, demand reduction	Guard against sink-to-source pulses after dry spells
Heatwaves	Higher liquor temperature, lower dissolved oxygen, evaporation	Odour, oxygen stress, salt and organic concentration, microbial decline	Shaded zones, deeper polishing ponds, diverse microbial habitat	Avoid stagnant water and uncontrolled anaerobic zones
Salinity intrusion	Higher conductivity in process and wastewater streams	Plant stress, microbial inhibition, biological instability	Salt-tolerant macrophytes, robust substrates, staged treatment	Pilot-test plant survival before scale-up
Power disruption	Pumps, aerators, and controls may fail	Loss of active biological treatment and sludge control	Gravity-fed buffers, passive polishing, emergency storage	Passive units are safety layers, not substitutes for treatment

Table 1 shows the main pathways through which climate stress affects industrial wastewater treatment and identifies the corresponding NBS resilience responses. The table indicates that each stressor needs a different design logic. Flooding requires freeboard, stormwater separation, modular cells, and emergency storage. Drought requires concentration management, reuse control, and protection against rewetting pulses. Heat requires shading, hydraulic circulation, and avoidance of stagnant anaerobic zones. Salinity requires salt-tolerant plant selection and local piloting. Power disruption requires passive safety layers such as gravity-fed buffers and emergency storage, but these cannot replace the core treatment system.

The planning implication is clear. NBS should not be added only as end-of-pipe greening. They must be designed around specific climate-stress pathways. A flood-resilient system needs hydraulic reserve. A drought-resilient system needs concentration control and reuse discipline. A salinity-resilient system needs biological selection and field testing. Therefore, climate-resilient NBS depend on both ecological function and engineering control.

NATURE-BASED OPTIONS APPRAISED AGAINST RESILIENCE FUNCTIONS

The option set

Constructed wetlands are the most mature NBS for wastewater treatment. Free-water-surface systems can provide habitat and landscape value, but subsurface systems are generally safer for industrial polishing because they reduce direct exposure to contaminated water. Vertical-flow wetlands support oxygen transfer and nitrification. Horizontal subsurface-flow wetlands support filtration and denitrification. Hybrid systems combine these pathways and are therefore better suited to variable industrial streams (Gikas and Tsihrintzis, 2012; Saeed and Sun, 2012; Stefanakis *et al.*, 2014). Earlier reviews and applications also show the value of constructed wetlands in developing countries and high-strength wastewater contexts when pretreatment and design envelopes are respected (Kivaisi, 2001; Scholz and Lee, 2005; Zhang *et al.*, 2015; Zhi and Ji, 2012).

Floating treatment wetlands suit ponds, lagoons, and reuse reservoirs. Their roots provide biofilm surfaces and trap particulates, but they remain supplementary and need anchoring, harvesting, and toxic-shock protection (Headley and Tanner, 2012; Tanner and Headley, 2011; Rezania *et al.*, 2015). Algal and algal-bacterial systems recover nutrients and produce oxygen, but they are sensitive to light, pH, temperature, toxicity, and harvesting limits (Chisti, 2007; Craggs *et al.*, 2014; Park *et al.*, 2011; Walters *et al.*, 2024).

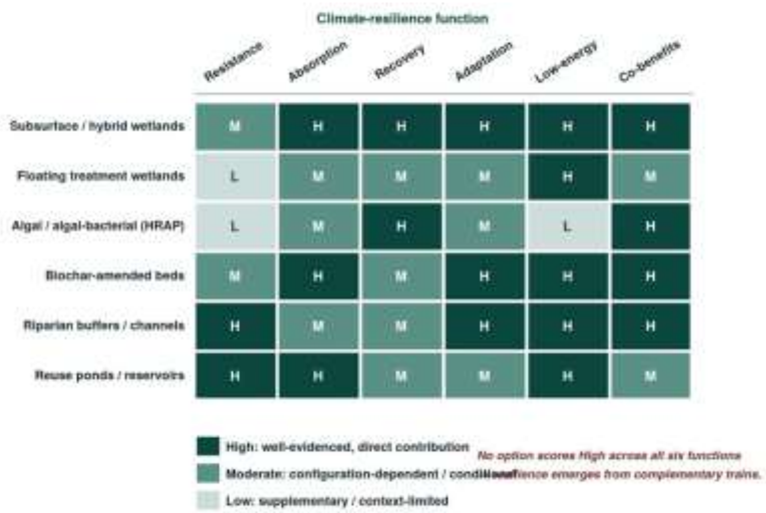

Fig. 3. Resilience appraisal matrix for six nature-based options across six climate-resilience functions

Biochar-amended beds are an important innovation area. Biochar can add adsorption capacity, microbial habitat, porosity, and carbon storage. Performance depends on feedstock, pyrolysis temperature, particle size, surface chemistry, aeration, and replacement rules (Karki *et al.*, 2024; Li *et al.*, 2025; Pandey *et al.*, 2025; Yang and Yang, 2024; Yu *et al.*, 2023). Riparian buffers, vegetated channels, reuse ponds, and storage reservoirs add catchment protection and hydraulic reserve (Ghermandi *et al.*, 2007; Maucieri *et al.*, 2020).

The resilience appraisal matrix

The resilience appraisal compares six NBS options against six resilience functions: resistance, absorption, recovery, adaptation, low-energy operation, and co-benefits. These scores are interpretive judgements based on the reviewed literature. They should not be read as statistical estimates. Their value is to show how different ecological options contribute to resilience in different ways.

Fig. 3 presents the appraisal matrix and shows that no single NBS option performs strongly across all resilience functions. Constructed wetlands provide a strong foundation for polishing, biological treatment, recovery, and low-energy operation, but they are vulnerable if uncontrolled floodwater enters the system. Reuse ponds and storage reservoirs provide stronger hydraulic buffering, especially during flood or drought periods. Biochar-amended beds add adsorptive capacity and shock-buffering potential, but they require replacement and contaminant management. Floating treatment wetlands and algal systems provide useful supplementary functions, but they remain sensitive to anchoring, harvesting, toxicity, light, pH, and temperature.

Table 2 translates this appraisal into design guidance for industrial wastewater systems. The table shows that each NBS option has a specific role in a treatment train. Subsurface and hybrid constructed wetlands are most suitable for secondary polishing and industrial-park treatment.

Floating treatment wetlands are useful for retrofitting ponds and reservoirs. Algal systems are more relevant for nutrient-rich effluent and resource recovery. Biochar beds are suited to adsorptive polishing for colour, metals, ammonium, and selected emerging pollutants. Riparian buffers and vegetated channels provide catchment-scale protection, while reuse ponds and storage reservoirs provide hydraulic reserve.

The main finding is that resilience comes from combination, not from a single technology. Constructed wetlands may anchor the system, but hydraulic reserve usually comes from storage. Adsorptive protection may come from biochar. Final catchment protection may come from buffers and vegetated channels. Co-benefits such as carbon storage, biodiversity, visible adaptation, and water reuse also become stronger when ecological units are arranged as part of a treatment train rather than installed as isolated units.

Table 2. Design guidance derived from the resilience appraisal

Nature-based option	Best industrial role	Dominant removal pathways	Resilience contribution	Representative evidence
Subsurface and hybrid constructed wetlands	Secondary polishing and industrial-park treatment	Sedimentation, filtration, adsorption, microbial degradation, plant uptake	Absorption, recovery, adaptation, low energy demand	Vymazal (2014); Wang *et al.* (2023); Javeed *et al.* (2025)
Floating treatment wetlands	Retrofit of ponds and reservoirs	Root-zone biofilm, nutrient uptake, solids capture	Low-civil-work polishing and visible adaptation	Tanner and Headley (2011); Rezania *et al.* (2015)
Algal and algal-bacterial systems	Nutrient-rich effluent and recovery	Algal uptake, photosynthetic oxygenation, biomass assimilation	Low-energy nutrient capture and carbon link	Craggs *et al.* (2014); Walters *et al.* (2024); Chisti (2007)
Biochar-amended beds and filters	Adsorptive polishing for colour, metals, ammonium, emerging pollutants	Adsorption, ion exchange, microbial habitat, redox support	Carbon storage and shock buffering	Pandey *et al.* (2025); Yu *et al.* (2023); Yang and Yang (2024)
Riparian buffers and vegetated channels	Catchment-scale final barrier after source control	Sediment trapping, plant uptake, infiltration, flow attenuation	Flood moderation and receiving-water protection	Masi *et al.* (2018); Ghermandi *et al.* (2007)
Reuse ponds and storage reservoirs	Hydraulic buffering and drought reserve	Storage, sedimentation, die-off, shock equalisation	High resistance and absorption	Ghermandi *et al.* (2007); Maucieri *et al.* (2020)

REMOVAL MECHANISMS AND SECTOR-SPECIFIC DESIGN LOGIC

Pollutant-removal mechanisms

Ecological treatment works through many pathways at once. Suspended solids settle and filter through media. Organic matter is degraded by microorganisms attached to gravel, sand, soil, biochar, roots, and sediments. Nitrogen shifts through ammonification, nitrification, denitrification, plant uptake, and microbial assimilation. Phosphorus is removed through adsorption, precipitation, sediment storage, and uptake, but retention weakens as media saturate (Saeed and Sun, 2012; Vymazal, 2007, 2010). This multiplicity creates redundancy, but it also creates climate sensitivity because living processes respond to heat, drought, toxicity, and salinity.

Metals require special caution. Wetlands and aquatic plants can remove metals through adsorption, precipitation, complexation, sedimentation, microbial transformation, and uptake.

This improves water quality but shifts the hazard into sediments, substrate, and biomass (Calheiros *et al.*, 2007, 2009; Rai, 2009). Recent textile mesocosm evidence showed removal of cadmium and chromium alongside strong metal accumulation in plant tissue, which makes biomass management part of treatment design (Javeed *et al.*, 2025). Textile toxicity reduction has also been observed in constructed wetland treatment, but this does not remove the need for source control and careful disposal (Baughman *et al.*, 2003).

Emerging contaminants are relevant where industrial and municipal streams mix. Constructed wetlands can remove selected pharmaceuticals and personal-care compounds through adsorption, biodegradation, photolysis, plant uptake, and sedimentation. Biochar can improve sorption and microbial habitat, but long-term field evidence remains limited under variable real-world operating conditions (Ávila *et al.*, 2015; Li *et al.*, 2014; Verlicchi and Zambello, 2014; Zhang *et al.*, 2016).

Sector-specific design logic

Textile and dyeing clusters are a priority because they are water-intensive, chemically variable, and often flood-exposed. Wetlands can reduce organics, solids, colour, and toxicity, but textile effluent cannot be treated as domestic-like wastewater. Equalisation, pH control, colour and toxicity management, and pilot testing are essential (Etana *et al.*, 2025; Hussein, 2023; Yaseen and Scholz, 2019).

Tannery effluent needs source segregation, chromium recovery, salinity control, and strong pretreatment before ecological polishing. Dairy, brewery, and food-processing streams are more biodegradable and may suit plant or algal recovery, but grease, odour, shock loads, and methane risk require warm-climate control (Kivaisi, 2001; Trujillo-García *et al.*, 2026). Refinery, petrochemical, pulp-and-paper, landfill leachate, and other high-strength streams require the greatest caution. Ecological treatment should follow strong pretreatment, toxicity monitoring, and bounded hydraulic and organic loading rates (Scholz and Lee, 2005; Vymazal, 2014; Wu *et al.*, 2014; Yalcuk and Ugurlu, 2009).

Operating envelope is therefore central. In hybrid wetland studies, removal did not increase endlessly with retention time; performance could decline when prolonged holding caused resuspension, concentration, fouling, or oxygen stress (Javeed *et al.*, 2025). The practical implication for South Asian textile clusters is simple: wetlands are not cheap substitutes for ETPs. They are protected polishing and buffering units placed after cleaner production, source control, equalisation, and conventional treatment.

MULTI-SCALE DESIGN AND GOVERNANCE MODEL

Five design layers

The first layer is risk diagnosis. Design begins with flow, pollutant profile, production variation, chemical use, toxicity, pH, salinity, temperature, receiving-water sensitivity, land, flood level, drought risk, groundwater condition, and reuse demand.

The second layer is load control through equalisation, screening, oil and grease removal, pH correction, primary treatment, and biological or chemical treatment where needed.

The third layer is treatment-train configuration. A robust train may include vertical-flow wetlands, horizontal-flow wetlands, biochar beds, floating wetlands, algae, and storage. The fourth layer is climate-proofing through freeboard, stormwater separation, modular cells, bypass protection, emergency storage, salt-tolerant plants, accessible sampling, gravity flow, and safe-to-fail overflow. The fifth layer is governance and monitoring, including trained operators, vegetation management, sediment removal, media replacement, sampling, biological-health checks, reporting, and firm cost-sharing rules.

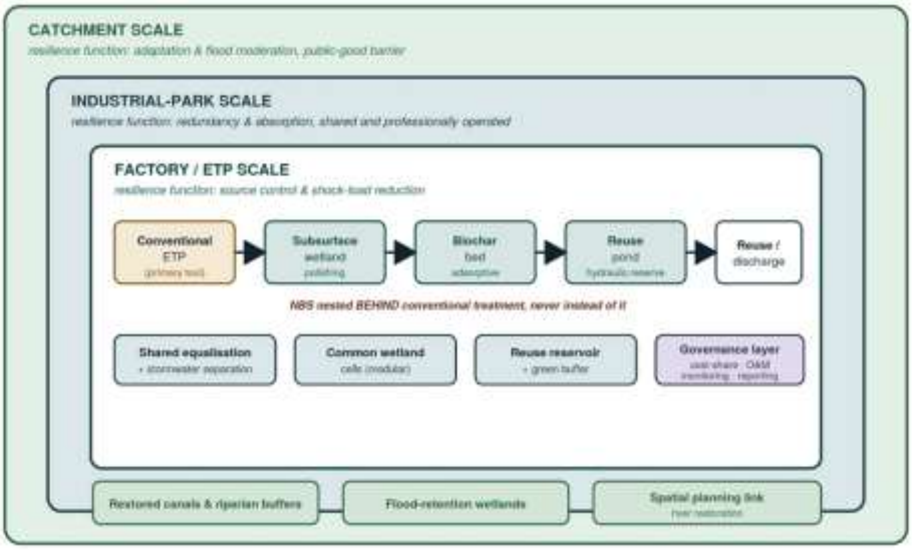

Fig. 4. Multi-scale integration model across factory, industrial-park, and catchment scales

Table 3. Five-layer design framework for climate-resilient industrial NBS

Design layer	Core question	Principal actions	Expected resilience outcome
1. Risk diagnosis	Which climate and wastewater risks must the system handle?	Assess pollutants, flow variability, flood level, salinity, toxicity, land, and reuse demand	Design anchored in real industrial risk
2. Load control	How are shock loads reduced before ecological treatment?	Equalisation, screening, pH correction, oil removal, primary and biological treatment	Plants, microbes, and substrates protected
3. Treatment train	Which NBS units match the pollutant profile?	Sequence vertical flow, horizontal flow, biochar, floating wetland, algae, and storage	Multiple removal pathways improve stability
4. Climate-proofing	How will the system behave under flood, heat, drought, and salinity?	Freeboard, modular cells, stormwater separation, salt-tolerant plants, emergency storage	Disturbance absorbed without major failure
5. Governance	Who will operate, monitor, fund, and repair the system?	O&M plan, sampling, harvesting, substrate replacement, cost-sharing, reporting	Long-term function survives installation

Nesting across three scales

Climate-resilient industrial wastewater management needs to be planned across three connected scales. At the factory scale, NBS should be placed after the ETP as monitored polishing units. Their purpose is to improve final effluent quality, provide limited buffering, and add biological redundancy. They should not be used to replace primary, chemical, or biological treatment where these are required.

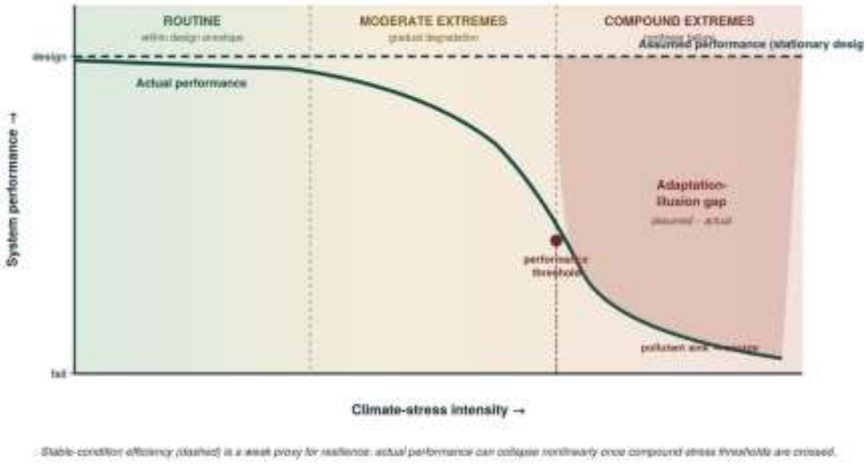

Fig. 5. The adaptation illusion: stable-condition efficiency is a weak proxy for resilience under compound climate stress

At the industrial-park scale, shared ecological polishing can serve several factories if each factory provides adequate pretreatment and influent control. This scale is important because land, monitoring, and maintenance costs can be shared. It also allows professional operation, common sampling points, equalisation, stormwater separation, reuse reservoirs, and modular wetland cells. In dense textile clusters, this scale may be more practical than expecting every small or medium factory to maintain a full ecological system separately.

At the catchment scale, restored canals, riparian buffers, retention wetlands, and vegetated channels provide the final public-good layer. These features cannot compensate for untreated discharge, but they can reduce residual pollution, slow floodwater, protect receiving water, and improve community confidence when upstream controls are in place.

Fig. 4 illustrates this nested model across factory, industrial-park, and catchment scales. Table 3 then converts the model into a five-layer design framework, beginning with risk diagnosis and moving through load control, treatment-train configuration, climate-proofing, and governance.

The two messages are closely connected. The physical design must be multi-scale, and the governance system must ensure that each scale continues to function after installation.

DISCUSSION

Main concerns and application pathway

The main concern emerging from this review is that treatment efficiency under stable conditions can create a false sense of resilience. A system may remove COD, BOD, suspended solids, nutrients, colour, or metals during normal operation, but this does not prove that it can protect receiving water during flood pulses, drought concentration, heat stress, salinity intrusion, or power disruption. Climate resilience therefore cannot be judged only by average removal performance. It must be judged by how the whole treatment system behaves when hydraulic, biological, and operational conditions are disturbed (Fig. 5).

This finding has a direct implication for technology selection. Industrial NBS should not be selected as single stand-alone units. A vertical-flow wetland can improve aeration, but it cannot manage all colour, salinity, or toxic-shock risks. A biochar bed can adsorb selected pollutants, but it will eventually saturate. An algal pond may support nutrient recovery, but it is sensitive to light, pH, temperature, and influent toxicity. A floating wetland can improve pond polishing, but it is not a complete treatment system. A stronger approach is hybrid grey-green design, where conventional treatment secures compliance and ecological units add polishing, absorption, reuse support, low-energy reserve, and co-benefits (Ahern, 2011; Masi *et al.*, 2018).

Circularity also needs caution. Treated effluent may support non-potable reuse where standards allow, and wetland biomass, algae, or biochar may offer recovery or carbon-storage value.

However, biomass grown in dye-, metal-, or chemical-bearing wastewater should not be reused casually in soil, feed, or agriculture. Spent substrate and biochar may also require controlled handling. Circularity becomes sustainable only when contaminant fate is traced and managed from removal to final disposal (Maucieri *et al.*, 2020; Yang and Yang, 2024).

Bangladesh provides a practical setting for this argument. Textile and ready-made-garment clusters operate in areas where river pollution, groundwater stress, drainage congestion, monsoon flooding, heat exposure, and production pressure already overlap. The key question is not only whether a factory has an ETP. The more important question is whether the treatment, drainage, polishing, and reuse system can continue to function under climate stress. Directly transferring NBS designs from temperate settings to tropical monsoon deltas may create new risks if local flood depth, land scarcity, pollutant strength, heat, salinity, and maintenance capacity are not considered (Alamdari, 2026; Esraz-Ul-Zannat *et al.*, 2024).

A staged application pathway is therefore more suitable. At factory scale, planted gravel filters, subsurface-flow wetlands, biochar beds, and floating systems can be used as monitored polishing units after existing ETPs. At industrial-park scale, shared ecological polishing can combine equalisation, wetland cells, reuse reservoirs, stormwater separation, and green buffers. At catchment scale, restored channels, riparian vegetation, and retention ponds can reduce residual pollution and slow floodwater. These interventions will work only when they are linked with regulation, buyer assurance, community trust, trained operation, and long-term maintenance.

FUTURE RESEARCH AGENDA

Future research should move beyond reporting treatment efficiency under stable operating conditions. Many studies still measure removal of COD, BOD, suspended solids, nutrients, colour, metals, or selected contaminants under ordinary loading. This is useful, but it does not show whether nature-based systems can continue to protect receiving water during flood pulses, drought concentration, heat stress, salinity intrusion, or power disruption. Future experiments should therefore test ecological treatment systems under climate-stress scenarios, including high hydraulic loading, prolonged dry periods, sudden rewetting, elevated temperature, salinity stress, and toxic shock. Drought-to-deluge sequences are especially important because they can reveal whether wetlands and other NBS remain pollutant sinks or temporarily become pollutant sources after disturbance (Alamdari, 2026).

Longer field monitoring is also needed. Many pilot studies operate for a few months, while real infrastructure must function for many years. Future studies should therefore report not only average removal efficiency, but also clogging, hydraulic conductivity, substrate exhaustion, seasonal plant health, microbial condition, biomass contamination, odour, greenhouse-gas emissions, maintenance cost, and failure events. This is important because long-term performance may decline even when early-stage results are promising (Nivala *et al.*, 2012; Vymazal, 2018).

A third research need is contaminant fate. Pollutants removed from water do not disappear from the system. Metals, dyes, nutrients, salts, organic compounds, and emerging contaminants may accumulate in roots, shoots, sediments, gravel, biochar, sludge, or harvested biomass. This issue is critical for textile, tannery, petrochemical, and mixed industrial wastewater, where recovered biomass or spent media may become contaminated waste. Future studies should therefore trace where pollutants move after removal and define safe rules for harvesting, reuse, replacement, and final disposal (Javeed *et al.*, 2025; Rai, 2009).

Future research should also strengthen life-cycle and cost assessment. NBS are often presented as low-energy and low-cost options, but their real sustainability depends on land requirement, construction materials, pumping need, media replacement, biomass handling, labour, monitoring, methane or nitrous oxide emissions, and possible carbon-storage benefits. Biochar-amended systems need particular attention because their climate value depends on feedstock source, pyrolysis process, transport distance, adsorption life, and disposal route (Maucieri *et al.*, 2020; Pandey *et al.*, 2025).

Finally, governance should become a central research theme. Industrial ecological treatment systems do not fail only because of technical weakness. They also fail when influent quality is uncontrolled, cost-sharing is unclear, monitoring is irregular, operators are not trained, or maintenance funds are absent. This is especially relevant for shared systems in industrial parks, where one factory's poor discharge can affect the whole treatment train. Future studies should examine institutional rules for pretreatment, emergency operation, public reporting, buyer recognition, community confidence, and regulatory enforcement. For Bangladesh and similar textile-producing regions, this governance evidence will be as important as the engineering evidence.

This future research agenda points to one broader need: nature-based solutions for industrial wastewater should be tested as climate-exposed infrastructure, not only as treatment units under normal conditions.

CONCLUSION

Nature-based solutions can strengthen industrial wastewater management under climate stress, but only when they are designed as engineered ecological infrastructure. Their value is not limited to low-cost treatment. They provide hydraulic buffering, ecological redundancy, final polishing, reduced energy dependence, carbon storage, reuse support, habitat, and visible adaptation. These benefits matter most where flood, heat, drought, salinity, water scarcity, and power disruption interact.

The central finding is that stable-condition treatment efficiency is a weak and sometimes misleading proxy for climate resilience. Resilience comes from complementary treatment trains and from nesting factory compliance, industrial-park governance, and catchment protection into one system. For Bangladesh and similar South Asian textile clusters, the immediate opportunity is to pilot ecological polishing behind existing ETPs, test performance across wet and dry seasons, document contaminant fate, and build credible governance. Industrial wastewater resilience will be strongest where engineering control and ecological intelligence are planned as one system.

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