

Innovation of Microbe-Based Bioremediation Systems for Reducing Environmental Pollution from Industrial Wastewater in Urban Areas: A Structured Narrative Review

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ABSTRACT

Urban industrial areas generate chemically complex wastewater containing dyes, heavy metals, petroleum hydrocarbons, organic matter, nutrients, and emerging contaminants. This narrative review synthesizes 26 peer-reviewed sources to evaluate microbe-based treatment options and develop a maturity-aware modular framework for urban industrial wastewater management. The corpus included 18 sources from the original manuscript and 11 candidates identified through a focused update search on 10 September 2026, with three excluded for redundancy or insufficient relevance. Representative studies reported 86–93.37% COD removal using staged alkaliphilic consortia in real textile wastewater, 99.32% oil-and-grease removal using an immobilized indigenous consortium in real batik wastewater, 89.5% COD and 94% petroleum-hydrocarbon removal in an oil-recycling plant, and up to 88% COD removal using microbial fuel cells for petrochemical wastewater. Established functions include equalization, conventional biological reactors, staged redox treatment, and routine monitoring, while specialized consortia and algae-bacteria polishing require site-specific validation. Bioelectrochemical systems, omics, AI-assisted control, and digital twins remain emerging. The proposed framework integrates source segregation, shock-load protection, adapted microbial treatment, selective polishing, residual management, governance, and regulatory verification. Pilot validation, life-cycle, techno-economic, biosafety, and regulatory assessments remain essential for full-scale deployment.

Keywords: *Microbial Bioremediation, Industrial Wastewater, Microbial Consortia, Immobilized Biofilm, Urban Pollution, Bioelectrochemical Systems, Narrative Review*



INTRODUCTION

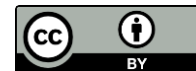
Rapid urbanization and industrial concentration intensify pressure on urban water bodies (Ayilara & Babalola, 2023) because industrial wastewater is often generated near densely populated settlements and is discharged into drainage networks, rivers, canals, or municipal wastewater systems. Industrial effluents are highly heterogeneous: textile and dyeing activities release colorants and salts; metal processing and electroplating generate heavy-metal-rich streams; petroleum-related activities release hydrocarbons; food and beverage production contributes high organic loads; and pharmaceutical and chemical industries add persistent or biologically active compounds. This heterogeneity makes treatment selection difficult because a single process rarely performs equally well for all pollutants. Kato and Kansha (2024) emphasized that wastewater characteristics differ substantially between industries and that treatment must therefore be matched to pollutant composition and process conditions.

Conventional treatment based on coagulation, precipitation, adsorption, membrane separation, advanced oxidation, or other physicochemical operations remains essential for many industrial applications. However, such processes may require substantial energy, chemical reagents, or replacement materials and can transfer contaminants from water to sludge or spent media rather than completely transforming them. Biological processes provide a complementary approach because microorganisms can use organic pollutants as carbon or energy sources, transform toxic chemicals, immobilize metals, and participate in nutrient conversion (Chatterjee et al., 2024). Reviews of industrial wastewater bioremediation identify bacteria, fungi, algae, and mixed microbial communities as important agents for pollutant detoxification and resource recovery (Saravanan et al., 2023; Abo-Alkasem et al., 2023).

The central challenge is that real industrial wastewater is chemically complex and operationally unstable. Toxic shocks, salinity, extreme pH, fluctuating flow, nutrient imbalance, and co-occurring contaminants can inhibit a single microbial strain. Recent research therefore increasingly favors microbial consortia and engineered communities. In textile wastewater, mixed cultures can distribute metabolic tasks across different organisms, enabling sequential transformation of dye molecules and toxic intermediates (Aragaw, 2024). Bacterial-microalgal consortia extend this principle by coupling bacterial degradation with photosynthetic oxygenation, nutrient uptake, and potential biomass recovery (Rathour et al., 2024).

A second major innovation is microbial immobilization. Retaining microorganisms on carriers, biofilms, porous matrices, or encapsulation materials can increase cell density, protect microorganisms from hydraulic washout, and improve resilience during toxic loading. New carrier concepts include biochar, composite media, nanostructured supports, and other high-surface-area materials (Hou et al., 2024; Ogundolie et al., 2024). These advances are especially relevant in urban industrial areas where treatment systems must be compact, stable, and capable of handling variable influent quality.

Technology maturity must be separated from scientific novelty. Equalization, conventional activated-sludge and biofilm reactors, anaerobic-aerobic staging, and routine online sensing are established wastewater-treatment functions. Advanced immobilized consortia and bacterial-microalgal systems have growing experimental and pilot evidence but remain more site-dependent. Bioelectrochemical systems (BES), including microbial fuel cells, are promising for simultaneous treatment and resource recovery, yet commercialization remains limited; a recent readiness assessment places most successful laboratory MFC demonstrations around technology readiness level (TRL) 4, with selected field studies at approximately TRL 5-7 rather than market-wide TRL 9 (Ieropoulos et al., 2024). Multi-omics, AI-assisted control, and digital-twin concepts are also progressing rapidly, but most



current evidence supports their use as diagnostic, predictive, or decision-support layers rather than as substitutes for validated process control and laboratory compliance testing (Renganathan et al., 2025; Renganathan & Gaysina, 2025; de Matos Filho et al., 2026).

The research gap is therefore one of engineering integration and deployment discipline rather than a lack of individual technologies. The specific contribution of this review is a maturity-gated modular design logic with six principles: (1) segregate or pretreat toxic sidestreams before biological exposure; (2) buffer variable loads through equalization; (3) use locally adapted or selected microbial consortia with biomass-retention strategies as the biological core; (4) apply staged redox conditions when pollutant chemistry requires sequential transformations; (5) select polishing and resource-recovery modules according to site constraints and evidence maturity rather than technological novelty alone; and (6) integrate residual management, monitoring, governance, cost-sharing, and regulatory verification into the treatment architecture. This distinguishes the proposed framework from hybrid systems that merely combine unit processes without an explicit pollutant-to-process decision rule, maturity gate, and cluster-governance layer.

METHODS

Review design and scope. This article used a structured narrative review combined with conceptual process design. The core publication window extended from January 2023 to 10 September 2026, with earlier sources retained only when needed to explain established mechanisms or engineering context. The review was designed to compare microbial treatment options across heterogeneous industrial wastewater matrices rather than to estimate a pooled effect size.

Search strategy. The original manuscript contained 18 peer-reviewed sources. For the revision, a focused supplementary search was conducted on 10 September 2026 using PubMed-indexed records and publisher platforms including ScienceDirect, SpringerLink, MDPI, and Wiley Online Library. Search terms included: "microbial bioremediation industrial wastewater", "microbial consortium textile wastewater COD", "immobilized bacterial consortium industrial wastewater", "algae bacteria industrial wastewater heavy metal", "microalgae bacteria biofilm wastewater nutrient removal", "microbial fuel cell industrial wastewater COD power density", "bioelectrochemical systems wastewater technology readiness", and "AI industrial wastewater treatment". Reference chaining from recent reviews was used to locate directly relevant primary studies and implementation evidence.

Eligibility and selection. Articles were included when they were peer-reviewed, available in English, and addressed industrial wastewater or a high-strength mixed wastewater with direct transfer relevance; evaluated microbial consortia, biofilms and microbial immobilization, biological redox staging, algae-bacteria systems, bioelectrochemical treatment, or monitoring/control; and reported either quantitative treatment performance or engineering evidence relevant to robustness, scale-up, readiness, cost, or implementation. Studies were excluded when they focused only on soil remediation, municipal wastewater without transferable industrial relevance, non-microbial treatment alone, purely theoretical AI applications without wastewater relevance, duplicate evidence, or insufficiently documented outcomes. The supplementary update identified 11 candidate articles; three were excluded after relevance screening and eight were added. The final narrative corpus therefore comprised 26 peer-reviewed sources: 19 reviews and perspectives and seven primary experimental, continuous, or pilot studies. Regulatory documents were assessed separately and were not counted as review articles.

Data extraction and synthesis. For primary studies, extracted indicators included wastewater type, reactor configuration, operating mode or scale, COD/BOD/color/nutrient/metal removal, hydrocarbon or phenol removal where relevant, and bioelectricity metrics for BES. Reviews were used



to characterize mechanisms, operational constraints, and technology maturity. Because pollutant matrices, scales, hydraulic conditions, and endpoints differed substantially, no statistical meta-analysis was performed. Quantitative values are therefore presented as study-specific evidence and should not be interpreted as directly comparable treatment guarantees. Evidence maturity was interpreted using an engineering hierarchy in which full-scale or long-duration continuous evidence was weighted more strongly for deployability than short-term laboratory or batch proof-of-concept results.

RESULTS

1. Industrial Pollutant Groups and Microbial Removal Mechanisms

The literature shows that microbe-based treatment is most effective when pollutant chemistry is matched with the appropriate biological mechanism. Organic compounds can be mineralized or transformed through microbial metabolism, whereas metals cannot be biodegraded and must instead be biosorbed, accumulated, precipitated, reduced, oxidized, or otherwise transformed into less mobile forms. Abo-Alkasem et al. (2023) described microbial heavy-metal removal through mechanisms including biosorption, bioaccumulation, and biotransformation. For organic pollutants, metabolic diversity becomes the central design asset.

Dye-containing effluents illustrate the need for sequential metabolism. Azo bonds can be reductively cleaved under low-oxygen or anoxic conditions, but the resulting aromatic amines may require subsequent aerobic oxidation. Dye wastewater also frequently contains salinity, alkalinity, and auxiliary chemicals that inhibit conventional biomass. Aragaw (2024) and Wadhawan et al. (2024) therefore highlight the value of alkaliphilic and halotolerant microorganisms, while Karthika et al. (2024) identify bacteria, fungi, algae, yeast, and consortia as complementary biological options for dye removal.

Petroleum hydrocarbons are commonly degraded by bacteria and fungi through oxygenase-mediated activation, beta-oxidation, ring cleavage, biosurfactant-assisted uptake, and related pathways. Emerging strategies include biostimulation, bioaugmentation, engineered metabolism, and bioreactor control (Karishma et al., 2024). Pharmaceutical residues and other micropollutants are more variable: some compounds are directly biodegradable, some are removed mainly by co-metabolism or sorption to biomass, and some remain persistent without advanced polishing. Reviews therefore recommend integrating biological treatment with suitable reactor configurations or hybrid processes for recalcitrant compounds (Mateescu et al., 2024; Dolatimehr et al., 2024; Jayasekara et al., 2025).

Table 1. Pollutant Classes, Microbial Mechanisms, and Design Considerations for Urban Industrial Wastewater

Pollutant Class	Typical Sources	Microbial Approach	Main Mechanism	Key Design Consideration
Synthetic dyes and colorants	Textile, printing, leather, chemical industries	Bacterial/fungal consortia; alkaliphiles; halotolerant microbes	Reductive bond cleavage followed by aerobic oxidation; enzyme-mediated transformation	Use staged anoxic-aerobic zones; control pH, salinity, and toxic intermediates
Heavy metals	Electroplating, metal finishing, mining-related	Metal-tolerant bacteria, fungi, biofilms	Biosorption, bioaccumulation, precipitation, redox transformation	Metals are not biodegraded; recovered biomass/sludge

Pollutant Class	Typical Sources	Microbial Approach	Main Mechanism	Key Design Consideration
	processing, batteries			requires safe handling
Petroleum hydrocarbons	Refineries, workshops, fuel handling, petrochemical industries	Hydrocarbon-degrading bacteria/fungi; biosurfactant producers	Oxidation, ring cleavage, beta-oxidation, co-metabolism	Provide suitable electron acceptors and nutrients; avoid toxic shock loads
Pharmaceuticals and micropollutants	Pharmaceutical plants, hospitals, chemical industries	Activated sludge consortia, biofilms, fungi, algae, electroactive microbes	Biodegradation, co-metabolism, sorption, redox transformation	Some compounds are recalcitrant and need hybrid polishing
High-strength organic matter and nutrients	Food, beverage, agro-processing, mixed industrial estates	Heterotrophs, nitrifiers, denitrifiers, anaerobic consortia, microalgae	Carbon oxidation, fermentation, methanogenesis, nitrification-denitrification, nutrient assimilation	Balance organic loading, oxygen, retention time, and nutrient ratios

2. Microbial Consortia and Immobilized Biofilms as the Core Innovation

The primary-study evidence confirms that high removal efficiencies are achievable, but performance varies strongly with wastewater composition, reactor configuration, loading, retention time, and study scale. Table 2 therefore summarizes representative quantitative indicators without pooling them. The strongest transfer evidence comes from continuous or real-wastewater studies, while short-duration batch and laboratory systems are treated as proof-of-concept rather than direct full-scale forecasts.

Table 2. Representative Quantitative Performance Indicators From Primary Studies Included in the Revised Synthesis

Technology / Study	Wastewater and Scale	Representative Quantitative Performance	Operational Note	Evidence Maturity
Staged alkaliphilic microbial consortium (Aragaw et al., 2024)	Real textile wastewater; continuous two-stage anaerobic/aerobic reactor	Color 96-98%; COD 86-93.37%; TKN 91-96%	Sequential redox treatment; alkaline/saline matrix	Continuous laboratory / pilot-oriented
Immobilized indigenous consortium on activated	Real batik wastewater; laboratory	Oil & grease 99.32%; BOD reduction 56.01%;	Carrier improved biomass retention; Indonesian industrial context	Laboratory proof-of-concept with



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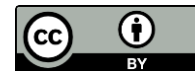
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Technology / Study	Wastewater and Scale	Representative Quantitative Performance	Operational Note	Evidence Maturity
geothermal silica (Yuniati et al., 2026)	comparison with free consortium	COD reduction 58.20%		real wastewater
Algae-bacteria consortium (Bashir et al., 2023)	Metal-polluted industrial wastewater; 14-day experimental treatment	COD 81.8%; BOD 66%; Mn 98.2%; Cu 94%; Cr 97.7%; Cd 91.6%; Pb 82.1%	Strong multi-pollutant removal; residual biomass needs safe handling	Batch experimental
Vertical rotating microalgae-bacteria biofilm (Yu et al., 2024)	Mixed soybean-soaking and municipal wastewater; sequential-batch and semi-continuous	Semi-continuous COD 98%, TN 95%, NH ₄ -N 99.9%; batch TP 97.6%	High nutrient removal; light and biomass harvesting remain constraints	Laboratory / semi-continuous
CSTR + trickling filter biotreatment (Jemli et al., 2025)	Used-oil recycling plant wastewater; long-duration continuous operation	TPH 94%; COD 89.5%; BOD ₅ 83.34%; phenol 91.25%	170-day operating evidence after start-up; strong industrial relevance	Industrial-site continuous evidence
Dual-chamber microbial fuel cell (Tamilarasan et al., 2024)	Petrochemical industrial wastewater; laboratory MFC	TCOD 88%; phenol 75%; sulphide 71%; max power density 270 mW/m ²	Good treatment performance but electrode/capital and scale-up constraints	Emerging laboratory BES
Indigenous bacterial remediation (Shah et al., 2025)	Industrial wastewater; bacterial treatment	<i>P. aeruginosa</i> : Cu 77.58-82.35%, Cd 19.67-50%, Pb 20.40-91.66%; <i>E. aerogenes</i> : Cu 47.05-60.61%, Cd 54.55-62.29%, Pb 85.21-91.6%	Metal-specific performance varied by organism and condition	Laboratory experimental

3. Engineering Robustness and Scale-Up Considerations

Across complex waste streams, microbial consortia offer functional redundancy and metabolic complementarity that single isolates often lack. One population can initiate xenobiotic transformation, another can consume intermediate products, and additional members can remove nutrients or detoxify inhibitory compounds. This principle is supported by multi-pollutant evidence: Bashir et al. (2023) reported simultaneous reductions in COD, BOD, and multiple metals using algae-bacteria consortia, while the Indonesian batik study of Yuniati et al. (2026) showed that immobilizing an indigenous bacterial consortium improved COD and BOD removal relative to a free consortium while maintaining



very high oil-and-grease removal. The practical advantage is therefore not only higher peak removal, but greater functional resilience across mixed contaminant loads.

Immobilization adds biomass-retention and shock-resistance benefits, but it introduces engineering liabilities that must be explicitly managed. Carrier fouling and clogging can increase head loss and create short-circuiting; excessive biofilm thickness can produce internal diffusion limitations and inactive zones; and carrier attrition or replacement creates recurrent material and residual-management costs. Long-term stability also depends on controlling shear, solids accumulation, pH, salinity, temperature, nutrient balance, and toxic shocks. Carrier selection should therefore be based on hydraulic durability, cleanability, replacement interval, mass-transfer performance, availability, biosafety, and end-of-life handling rather than laboratory removal efficiency alone (Hou et al., 2024; Ogundolie et al., 2024; Yuniati et al., 2026).

For full-scale implementation, the preferred consortium should be selected using real effluent rather than synthetic media alone. Selection criteria should include recovery after repeated toxic shocks, stability across seasonal and production changes, absence of unacceptable pathogenic or antimicrobial-resistance risks, compatibility with downstream reuse or discharge, and the ability to maintain performance under realistic hydraulic loading. Locally adapted biomass from existing treatment systems can provide a practical inoculum source, followed by controlled enrichment, carrier compatibility testing, and staged pilot verification before deliberate bioaugmentation.

4. Proposed Modular Microbe-Based Bioremediation System

The proposed framework comprises a compact, multi-barrier treatment train for individual factories or shared urban industrial clusters. Module 1 is source segregation and characterization: highly toxic, saline, metal-rich, solvent-rich, or concentrated sidestreams are isolated or pretreated so that dilution is not used as a substitute for pollution control. Module 2 is equalization, which buffers flow, pH, temperature, conductivity, and pollutant concentration and protects downstream biology from shock loads. These functions are mature and should precede advanced biological modules regardless of the novelty of later technologies.

Module 3 is the biological core: an adaptive consortium reactor with suspended-attached growth or immobilized biofilms on durable carriers. Moving-bed, packed-bed, trickling-filter, or hybrid configurations can be selected according to solids, footprint, maintenance capacity, and hydraulic behavior. For dyes and other redox-sensitive contaminants, Module 4 separates anoxic/anaerobic and aerobic conditions so reductive bond cleavage is followed by oxidation of intermediates. Aragaw et al. (2024) demonstrated the practical logic of this sequence, with 96-98% color removal and 86-93.37% COD removal in real textile wastewater.

Module 5 is site-dependent polishing. Established biofilm or membrane-biological options are appropriate when reliable compliance and compact footprint dominate, whereas bacterial-microalgal polishing can be considered when nutrient recovery, sunlight availability, and biomass harvesting are feasible. The high nutrient and COD removals reported by Yu et al. (2024) demonstrate technical potential, but lighting, harvesting, seasonal variability, land geometry, and downstream biomass use make algae-bacteria systems less universally mature than conventional biofilm polishing.

Bioelectrochemical treatment is treated as an optional emerging add-on rather than a mandatory core barrier. Laboratory studies and recent reviews show that MFCs can achieve high COD removal while generating electricity and support broader wastewater-refining concepts (Kunwar et al., 2024; Chu et al., 2025); for example, Tamilarasan et al. (2024) reported 88% total COD removal and 270 mW/m² maximum power density with petrochemical wastewater. However, current commercialization



reviews indicate that most MFC evidence remains at laboratory TRL, with selected field demonstrations at intermediate TRLs and insufficient industrial-scale evidence for routine deployment (Ieropoulos et al., 2024). Electrode cost, internal resistance, biofilm stability, power density, maintenance, and scale-up therefore remain decision constraints.

Monitoring is layered according to maturity. Flow, pH, dissolved oxygen, oxidation-reduction potential, temperature, conductivity, and validated organic-load surrogates are the core operational sensors, supported by periodic laboratory analysis for COD, BOD, nutrients, metals, target organics, toxicity, and microbial safety. Omics and eDNA can be used periodically for troubleshooting or community characterization, while AI and digital-twin models should initially function as decision-support tools with verified data quality, cybersecurity, and human oversight. Their value is highest when they improve early warning and control decisions, not when they replace legally required measurement or validated process control (Renganathan et al., 2025; de Matos Filho et al., 2026).

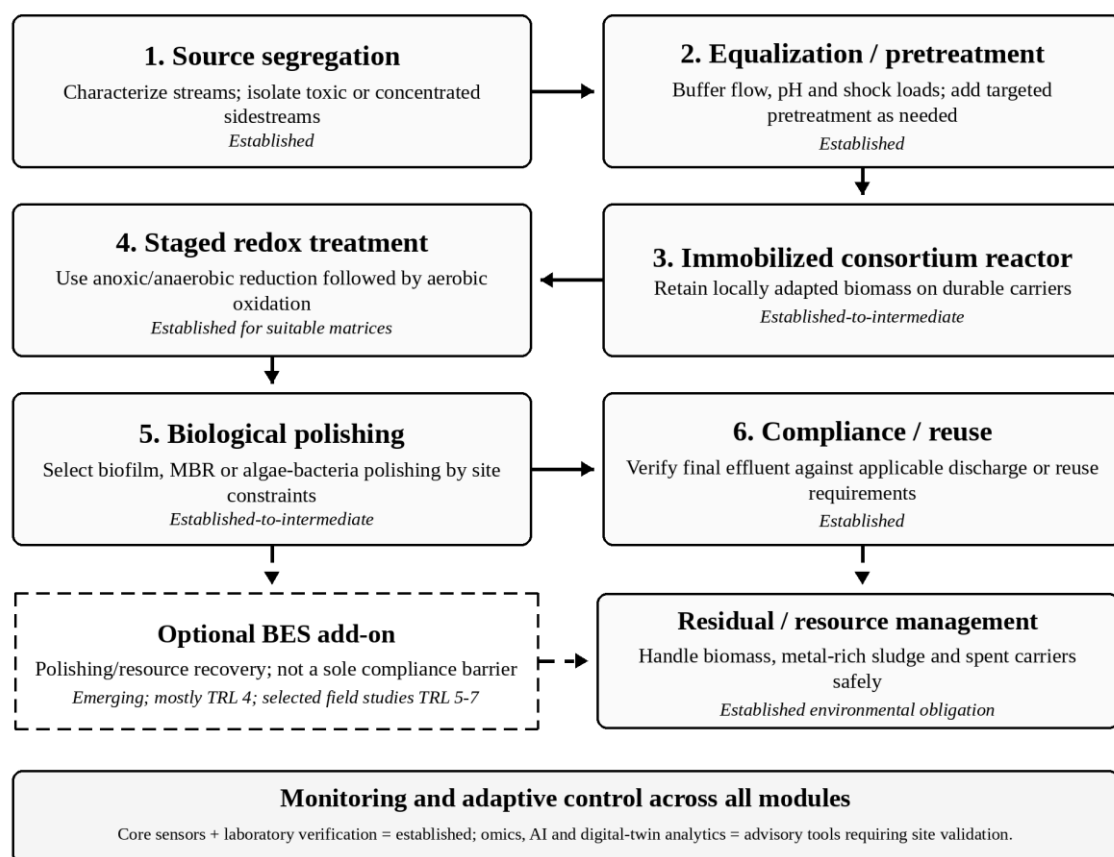


Figure 1. Maturity-Aware Modular Architecture for Urban Industrial Wastewater Treatment. Solid arrows indicate the core treatment pathway; dashed arrows indicate optional, emerging, or residual-management pathways. Monitoring and adaptive control apply across all modules.

Table 3. Maturity-Aware Modules, Operating Profile, and Implementation Constraints of the Proposed System

Module / Layer	Primary Function	Maturity	Operational / Cost Profile	Key Condition
1. Source segregation	Isolate toxic or concentrated sidestreams before biological treatment	Established	Characterization and selective pretreatment add cost	Define source profiles and internal acceptance limits
2. Equalization / pretreatment	Buffer flow, pH, temperature, salinity and shock loads	Established	Tankage, mixing, instrumentation and targeted pretreatment	Size for variability; prevent bypass and toxic shocks
3. Immobilized consortium reactor	Bulk organic/xenobiotic transformation and biomass retention	Established to intermediate; carrier/consortium dependent	Carrier replacement and fouling control add cost; compact footprint may be possible	Carrier durability, mass transfer, clogging control and long-term stability
4. Staged anoxic-aerobic treatment	Sequential transformation of dyes/redox-sensitive compounds	Established for suitable industrial matrices	Aeration is a major OPEX driver; staging can reduce toxicity	Redox control, HRT, aeration efficiency and intermediate toxicity
5. Biological polishing	Residual COD/nutrients and site-specific resource recovery	Established for conventional biofilm/MBR; intermediate for algae-bacteria systems	MBR has energy/membrane cost; algae add light and harvesting needs	Select by land, discharge target, energy price and biomass handling
6. Compliance / reuse	Verify final effluent against applicable discharge or reuse requirements	Established	Routine laboratory verification and validated online monitoring	Apply relevant sector-specific discharge or reuse requirements
Optional BES add-on	Polishing and energy/resource recovery	Emerging; mostly TRL 4; selected field evidence TRL 5-7	Electrodes, separators, maintenance and low power density affect economics	Pilot and techno-economic assessment before deployment; not a sole compliance barrier



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Module / Layer	Primary Function	Maturity	Operational / Cost Profile	Key Condition
Cross-cutting monitoring + analytics	Early warning, process control and performance verification	Sensors/lab verification established; omics/AI/digital twin emerging advisory layers	Calibration, data infrastructure and skilled staff are key cost drivers	Validated data, cybersecurity, model validation and human oversight
Cross-cutting residual/resource management	Prevent transfer of pollution to solids and recover resources only when safe	Established environmental obligation	Dewatering, classification, transport, regeneration and recovery costs vary by contaminant	Contaminant-specific characterization and compliant handling/disposal

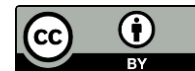
5. Operational Strategy, Governance, and Regulatory Compliance in Urban Industrial Areas

Urban deployment requires a different design logic from isolated remediation sites. Land, odor, noise, traffic, and mixed tenant schedules can constrain treatment more strongly than maximum laboratory removal. A modular system may operate as an in-factory unit for a single high-load industry, a shared cluster facility for small and medium enterprises, or a pretreatment-and-polishing arrangement linked to a municipal or industrial-estate system. The cluster model is attractive when individual enterprises cannot sustain advanced operation, but it is viable only if influent acceptance limits, pretreatment responsibilities, liability, emergency response, and data ownership are defined before commingling streams.

Robustness should be prioritized over peak removal. Equalization capacity, bypass prevention, standby aeration, redundant pumps, nutrient supplementation, spare carriers, cleaning access, simple operator dashboards, and routine activity/toxicity tests may contribute more to real-world reliability than highly optimized but fragile microbial cultures. Staffing should include competence in biological process control, sampling, basic microbiology, instrumentation, hazardous residual handling, and emergency isolation. Long-term performance contracts should include carrier inspection/replacement, sensor calibration, sludge/residual removal, and periodic verification of microbial and chemical stability.

Governance and cost-sharing are central for a shared cluster facility. A practical model is a jointly appointed or third-party operator governed by service-level agreements that specify allowable influent quality, monitoring frequency, data access, non-compliance response, and financial responsibility for toxic shocks. Tariffs should not rely only on wastewater volume; a hybrid fee can combine fixed infrastructure cost with variable charges based on flow and pollution load (for example COD, TSS, salinity, metals, or other sector-relevant parameters). This creates an incentive for source reduction and prevents low-pollution tenants from cross-subsidizing high-strength or toxic dischargers. Capital renewal, emergency reserve funds, and residual-disposal costs should be explicitly allocated.

For Indonesian application, the framework must be nested within the current environmental-approval and wastewater-control system. Government Regulation (PP) No. 22 of 2021 provides the overarching framework for environmental approval, water-quality protection, wastewater control, supervision, and



environmental compliance. Sector-specific standards then determine relevant effluent requirements; for example, textile wastewater is currently regulated by Regulation of the Minister of Environment/Head of the Environmental Control Agency No. 12 of 2025. A shared industrial facility should therefore establish internal acceptance limits and pretreatment obligations that are compatible with each tenant's environmental approval and enable the combined final effluent to meet the applicable discharge or reuse requirements. The framework should be updated whenever sector-specific or local standards change (Government of Indonesia, 2021; Ministry of Environment/BPLH, 2025).

Residuals management is part of compliance rather than an afterthought. Biomass that accumulates metals or persistent pollutants cannot automatically be classified as safe fertilizer or general organic waste. Metal-rich sludge, spent carrier media, and contaminated biomass require characterization and compliant recovery, stabilization, transport, or disposal. Clean biomass recovery should be pursued only when contaminant and biosafety criteria are met; otherwise, a treatment system may merely shift pollution from water to solids.

DISCUSSION

Comparative selection and technology readiness. The revised evidence shows that no single microbial process is preferable under all industrial conditions. Conventional suspended or attached-growth biology is the default when biodegradable COD removal and proven operability dominate. Immobilized consortia are preferable when biomass washout, toxic shocks, or a compact footprint are major constraints, but only when fouling, carrier life, and mass transfer can be maintained. Staged anoxic-aerobic treatment is particularly suitable for redox-sensitive pollutants such as azo dyes because reduction and subsequent oxidation perform different chemical functions. Algae-bacteria polishing becomes attractive where nutrient recovery, light, and biomass harvesting are feasible. BES should be reserved for research, pilot, or targeted resource-recovery applications until industrial-scale reliability and economics improve.

The quantitative evidence reinforces the need to separate removal efficiency from deployability. High laboratory performance can exceed 90% for COD, color, nutrients, or selected metals, yet long-duration industrial evidence is less common. Jemli et al. (2025) is especially informative because the reported CSTR/trickling-filter system operated for an extended period at an oil-recycling plant and achieved 94% TPH, 89.5% COD, 83.34% BOD₅, and 91.25% phenol removal. By contrast, several advanced consortia, microalgal, and BES studies remain laboratory or semi-continuous demonstrations. Consequently, scale-up decisions should weight duration, real-wastewater exposure, loading stability, operator requirements, and residual toxicity alongside percentage removal.

Economic feasibility. The proposed system should not be assumed to be universally cheaper than physicochemical treatment. Biological processes can reduce chemical consumption and sludge generation for biodegradable pollutants, but aeration, pumping, carrier replacement, membrane fouling, biomass harvesting, instrumentation, and skilled labor can become dominant operating costs. Equalization and source segregation increase upfront capital but can lower downstream reactor oversizing and shock-related failures. Immobilized systems may reduce footprint but add carrier procurement and replacement costs. Algal polishing may reduce aeration demand but can shift cost to land/light management and harvesting. BES introduces electrode, separator, and maintenance costs while present electricity production is generally insufficient to justify deployment on energy revenue alone. Omics and AI can reduce diagnostic delay or optimize operation, but only if savings from avoided failure or energy/chemical optimization exceed data, sensor, computing, and specialist costs. A site-



specific techno-economic assessment should therefore compare CAPEX, OPEX, energy, chemicals, residuals, land, downtime risk, and compliance risk over the life cycle.

Novelty of the framework. The contribution of this manuscript is not the invention of microbial consortia, biofilms, anoxic-aerobic treatment, microalgae, BES, or AI individually. The novelty is the integration logic: pollutant characterization precedes technology selection; established unit operations form the compliance backbone; locally adapted biomass and immobilization are used to increase resilience where justified; redox staging is selected according to contaminant transformation pathways; emerging technologies are maturity-gated as optional add-ons rather than presented as equivalent to mature processes; and monitoring, residual management, governance, cost-sharing, and regulation are treated as design modules. This combination makes the framework specifically suited to land-constrained urban industrial clusters with heterogeneous tenants and variable pollutant loads.

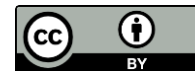
Regulatory, biosafety, and operational feasibility. For near-term implementation, naturally occurring or locally enriched non-pathogenic communities in contained reactors are more practical than environmental release of genetically engineered microorganisms. Sites should define biomass containment, disinfection when required, antimicrobial-resistance surveillance where relevant, and stop-work criteria for abnormal microbial or toxicity signals. Cluster governance must also establish responsibility for non-compliant influent and toxic shocks. In Indonesia, the applicable environmental approval and sector-specific effluent standards should be treated as binding design inputs rather than post-design checks. This makes regulatory verification a continuous operational function, not only an end-of-pipe sampling event.

Limitations and future research. This is a structured narrative synthesis rather than a systematic review or meta-analysis; the original manuscript did not retain a complete database-export log. Accordingly, the revised manuscript does not reconstruct unverifiable historical search counts and instead reports only the traceable original corpus and the focused supplementary update. The reviewed primary studies are heterogeneous in wastewater matrix, scale, duration, and performance endpoints. Future work should prioritize multi-month pilots on real mixed industrial wastewater; repeated shock-load testing; carrier life and regeneration; transformation-product and toxicity tracking; antimicrobial-resistance and biosafety surveillance; greenhouse-gas and energy accounting; full mass balances; and comparative techno-economic/life-cycle analyses. For shared industrial clusters, research should additionally evaluate pollutant-load-based tariffs, governance models, operator skill requirements, and compliance performance under multi-tenant variability.

CONCLUSIONS

Key findings and applicability. Microbe-based treatment can achieve substantial removal of organic pollutants, color, nutrients, hydrocarbons, and selected metals from industrial wastewater, but the evidence does not support treating all microbial innovations as equally mature. The most defensible urban-industrial configuration uses established source segregation, equalization, validated biological/biofilm treatment, staged redox operation where chemically appropriate, and laboratory-supported compliance monitoring as the core. Specialized immobilized consortia and algae-bacteria polishing can enhance resilience or resource recovery when site conditions justify them, while BES, omics, AI, and digital-twin functions should currently be deployed as pilot, diagnostic, or advisory layers unless stronger industrial validation is available.

Contribution and future priorities. The proposed novelty is a maturity-gated, pollutant-to-process architecture that combines microbial ecology with engineering robustness, residual management, governance, cost-sharing, and regulatory verification. It is potentially applicable to



individual factories and shared urban industrial clusters, including Indonesian settings, provided the design is validated against real wastewater and applicable environmental approvals and sector-specific effluent standards. Future research should move beyond short-term removal percentages toward long-duration pilots reporting mass balance, toxicity, energy and chemical use, sludge/residual generation, microbial stability, operating cost, and compliance reliability. These data are necessary before claiming full-scale technical or economic superiority over established treatment alternatives.

ACKNOWLEDGMENT

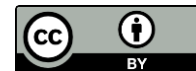
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