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Advanced Chemical and Hybrid Strategies for Industrial Wastewater Reuse: Catalysts, Modular Pods, and Smart Integration

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Abstract : Industrial wastewater is both an environmental liability and a potential resource stream. This review highlights frontier chemistry-driven technologies that simultaneously enable pollutant degradation and resource recovery. Advanced oxidation processes (AOPs) such as Fenton, photo-Fenton, and ozonation, along with catalytic wet air oxidation (CWAO) and electrochemical treatments, are evaluated for their capacity to eliminate persistent pollutants and reclaim valuable metals. Industrial residues including red mud, sludge, and agricultural by-products are examined as low-cost precursors for catalysts and adsorbents, reinforcing circular waste-to-resource strategies. A central contribution of this work is the proposal of modular "reaction pods"—decentralized, skid-mounted treatment units that integrate photochemical, electrochemical, and adsorption modules with real-time pH/redox sensors and IoT-enabled control systems. Green solvent extraction methods, including deep eutectic solvents and hybrid chemico-biological approaches, are assessed for selective recovery of dyes, metals, and pharmaceuticals. Case studies from petrochemical, textile, and institutional wastewater highlight the applicability of these integrated packages. Finally, we present a vision for scaling through digital twin frameworks and industry–academia partnerships. Together, these advances outline a circular and scalable framework for industrial liquid waste management, grounded in sustainable chemistry and intelligent systems engineering.

***IndexTerms* - Industrial liquid waste; Advanced oxidation processes; Resource recovery; Modular treatment pods; Circular economy; Digital twins**

1. INTRODUCTION

Global industrialization has generated massive volumes of liquid effluents containing heavy metals, dyes, surfactants, and persistent organic pollutants (POPs), which present significant environmental and public health risks. Conventional treatment methods—such as sedimentation, neutralization, and biological degradation—are often inadequate, as they demand high energy inputs, fail to achieve complete remediation, and frequently generate secondary waste streams (Fu & Wang, 2011; Sharma *et al*., 2020). In parallel, escalating freshwater demand and increasingly stringent environmental regulations are driving industries to adopt treatment strategies that emphasize **resource recovery alongside pollution control** (Verma *et al*., 2019; Kümmerer, 2016).

Chemistry-driven innovations are enabling a transition from linear "treat-and-dispose" approaches to circular frameworks that valorize waste as a resource. Advanced oxidation processes (AOPs)—including Fenton, photo-Fenton, ozonation, UV/H_2O_2, photocatalysis, and electrochemical oxidation—have demonstrated high efficiency in degrading refractory pollutants that resist conventional methods (Oturan & Aaron, 2014; Deblonde *et al*., 2011; Martínez-Huitle & Ferro, 2006). At the same time, emerging **green solvent-based separations**, particularly deep eutectic solvents (DESs) and ionic liquids (ILs), are showing promise in selectively recovering metals, dyes, and pharmaceuticals from complex wastewaters (Smith *et al*., 2014; Abbott *et al*., 2017).

Equally important is the valorization of **industrial by-products**. Residues such as fly ash, red mud, and agricultural wastes can be transformed into low-cost catalysts and adsorbents, closing material loops and reducing operational costs (Yadav *et al*., 2020; Mohan *et al*., 2014). These waste-derived materials integrate seamlessly into advanced treatment processes, enhancing both environmental and economic sustainability.

A particularly novel concept explored in this review is the development of **modular "reaction pods"**—decentralized, skid-mounted treatment systems that combine photochemical, electrochemical, and adsorption modules with real-time monitoring and adaptive control. These smart, flexible systems offer scalable, site-specific wastewater treatment solutions, particularly for remote or variable industrial operations.

This review critically evaluates these strategies across three key dimensions:

1. **Advanced chemical treatments** for refractory pollutants.
2. **Resource recovery and waste valorization** through low-cost catalysts and green solvents.
3. **System integration** via modular pods and digital twin-enabled monitoring for circular, intelligent wastewater management.

By linking fundamental chemistry with applied engineering, this work outlines a framework for **circular, scalable, and sustainable industrial liquid waste management**.

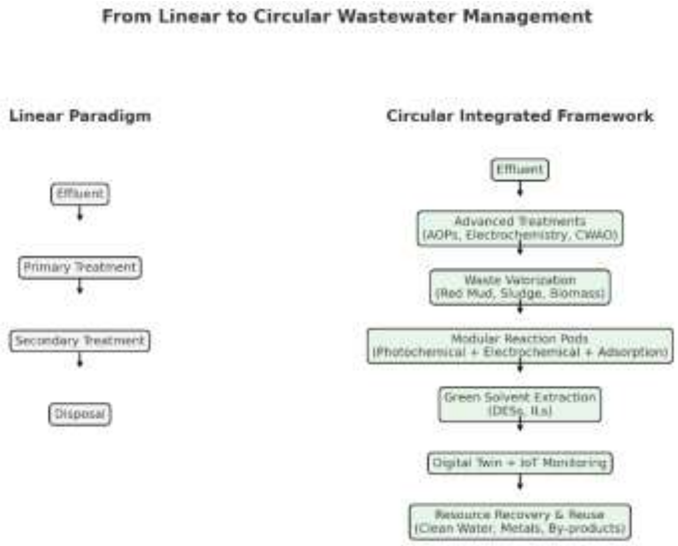

Figure 1. Transition from Linear to Circular Industrial Wastewater Management Framework

2. ADVANCE CHEMICAL TREATMENTS FOR INDUSTRIAL WASTE WATER

Industrial effluents often contain refractory pollutants such as dyes, phenols, surfactants, and heavy metals, which are difficult to degrade using conventional methods. Advanced chemical processes have therefore been developed to enhance oxidation, mineralization, and selective removal of contaminants while minimizing secondary waste generation. The most prominent categories include **advanced oxidation processes (AOPs), catalytic wet air oxidation (CWAO), and electrochemical treatments**.

2.1 Advanced Oxidation Processes (AOPs)

AOPs rely on the in-situ generation of highly reactive hydroxyl radicals (•OH) and other reactive oxygen species, which non-selectively oxidize complex organic molecules into simpler, less harmful compounds (Oturan & Aaron, 2014).

- **Fenton and Photo-Fenton Processes**: The classical Fenton process uses Fe^{2+} and H_2O_2 to generate radicals, while the photo-Fenton variant employs UV or visible light to accelerate iron cycling and improve mineralization efficiency. These methods are effective for dye-laden textile effluents, pharmaceuticals, and phenolic wastewater (Nidheesh & Gandhimathi, 2012).
- **Ozonation**: Ozone (O_3) reacts with unsaturated bonds and aromatic rings, making it efficient in color and toxicity removal. Its integration with UV or catalysts improves reaction rates but incurs high operational costs (Kasprzyk-Hordern *et al*., 2003).
- **UV/H_2O_2 and Photocatalysis**: Ultraviolet activation of H_2O_2 or semiconductor photocatalysts (e.g., TiO_2, ZnO) generates hydroxyl radicals, offering efficient degradation of pharmaceuticals and endocrine-disrupting compounds (Malato *et al*., 2009).

2.2 Catalytic Wet Air Oxidation (CWAO)

CWAO employs oxygen or air under elevated temperature (150–320 °C) and pressure (5–20 MPa), often with catalysts, to oxidize dissolved organics. It is particularly effective for high-strength effluents such as petrochemical sludge, resin waste, and dye wastewaters (Luck, 1999). Recent advances include the use of waste-derived catalysts (e.g., red mud, biochar-supported metals), which improve activity while lowering cost (Yadav et al., 2020).

2.3 Electrochemical Processes

Electrochemical treatments are modular, adaptable, and well-suited for decentralized treatment. Depending on the electrode material and applied current, they can achieve both pollutant degradation and resource recovery (Martínez-Huitle & Ferro, 2006).

- **Electrocoagulation:** Generates coagulant species (e.g., Al^{3+}, Fe^{3+}) in situ, destabilizing and removing suspended solids, oils, and heavy metals (Mollah et al., 2004).

- **Electro-oxidation (Anodic Oxidation):** Employs high-oxygen-overpotential anodes (e.g., boron-doped diamond, Ti/RuO_2) to directly oxidize pollutants or produce hydroxyl radicals. It is particularly effective for complete mineralization of pharmaceuticals and dyes (Martínez-Huitle & Brillas, 2009).
- **Electro-Fenton:** Generates H_2O_2 at the cathode, which reacts with Fe^{2+} to drive a continuous Fenton process, offering high efficiency with less chemical input (Oturan & Aaron, 2014).

Table 1: Comparative Overview of Advanced Chemical Treatments for Industrial Wastewater

Process	Mechanism	Target Pollutants	Advantages	Limitations	Typical Applications
Fenton / Photo-Fenton	$Fe^{2+} + H_2O_2 \rightarrow \bullet OH$	Dyes, phenols, pharmaceuticals	High efficiency, simple chemistry	Sludge generation, acidic pH required	Textile & pharma wastewater
Ozonation	O_3 + pollutants (direct/indirect oxidation)	Aromatic & unsaturated organics, dyes	Strong oxidant, effective for color removal	High cost, low solubility	Textile, pulp & paper
UV/H_2O_2 / Photocatalysis	UV light activates H_2O_2 or semiconductors	Refractory organics, EDCs	Complete mineralization possible	Requires UV, catalyst recovery	Pharma & municipal wastewater
CWAO	Oxidation under high T, P with catalyst	Sludge, petrochemical effluents	Effective for high-strength waste	Capital intensive	Petrochemical & resin industry
Electrocoagulation	In-situ coagulant generation	Suspended solids, metals, oils	Low chemical input, simple	Electrode passivation	Metal plating, tanneries
Electro-oxidation / Electro-Fenton	Anodic oxidation, cathodic H_2O_2 generation	Dyes, pharmaceuticals, POPs	High efficiency, complete mineralization	High energy demand	Hospital & textile wastewater

Critical Insights

While these treatments are powerful, their limitations include **energy demand (electrochemical systems), sludge generation (Fenton), and capital cost (ozonation, CWAO)**. Integration with **waste-derived catalysts, renewable electricity**, and **process intensification** (e.g., coupling with photocatalysis or membranes) are emerging pathways to overcome these bottlenecks.

3. RESOURCE RECOVERY AND VOLARIZATION OF INDUSTRIAL BY-PRODUCTS

Beyond pollutant degradation, a transformative strategy in industrial wastewater management is the **valorization of solid and semi-solid by-products** into functional materials. This approach not only reduces disposal burdens but also generates low-cost catalysts, adsorbents, and value-added products that feed back into treatment cycles, supporting a circular economy model.

3.1 Utilization of Industrial Residues

- **Red Mud:** A major by-product of alumina production, red mud is rich in Fe_2O_3, Al_2O_3, and TiO_2. Its high alkalinity makes it challenging to dispose of, yet it has been successfully repurposed as a catalyst for Fenton-like reactions and as an adsorbent for heavy metals (Yadav et al., 2020).
- **Sludge:** Wastewater treatment sludge, after thermal or chemical activation, yields carbon-rich materials (biochar, activated carbon) with high adsorption capacities for dyes and metals (Mohan et al., 2014).
- **Agricultural Waste:** Residues such as rice husks, coconut shells, and corn stalks can be pyrolyzed into biochar or chemically activated to enhance porosity, producing cost-effective alternatives to commercial adsorbents (Foo & Hameed, 2009).

3.2 Development of Low-cost Catalysts and Adsorbents

Recent advances focus on designing **waste-derived hybrid materials** that combine bio-based carriers with metal oxides or nanoparticles to enhance surface area, redox activity, and stability.

- **Metal-loaded biochars**: Incorporation of Fe, Mn, or Cu improves catalytic degradation of dyes and phenols (Zhu *et al.*, 2019).
- **Iron-based composites**: Effective in AOPs and electro-Fenton setups due to high reactivity and recyclability (Liu *et al.*, 2018).

- **Hybrid materials**: Integrating agricultural biochar with graphene oxide or TiO_2 nanoparticles boosts adsorption and photocatalytic performance (Gong *et al*., 2022).

3.3 Circular Economy in Practice

The valorization of industrial residues represents a closed-loop strategy, shifting industries from the conventional “produce–use–dispose” model to a “waste–reprocess–reuse” cycle.

- This reduces treatment costs, diverts waste from landfills, and creates new revenue streams from **secondary raw materials**.
- Industries can achieve compliance with environmental standards while also aligning with global **sustainable development goals (SDGs 6, 12, 13)**.

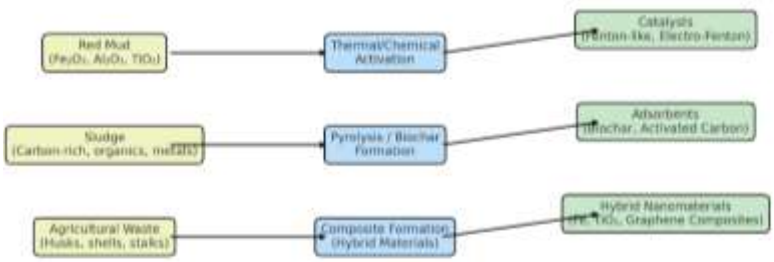

Figure 2. Waste-to-Resource Valorization Pathways

4. Modular Treatment Systems: “Reaction Pods” for On-site Wastewater Management

Industrial wastewater is highly heterogeneous, with compositions that vary across sectors and even within individual facilities depending on operational cycles. Such variability limits the efficiency of centralized, one-size-fits-all treatment approaches. A promising alternative is the deployment of **modular, decentralized treatment units**, or “*reaction pods*,” which integrate multiple processes into compact, skid-mounted systems designed for on-site use.

4.1 Design and Integration of Treatment Units

Reaction pods combine diverse treatment modules into a flexible package that can be tailored to specific wastewater profiles:

- **Photochemical Units**: Harness UV or visible light to drive photocatalysis, photo-Fenton reactions, or photolysis, enabling degradation of refractory organics (Malato *et al*., 2009).
- **Electrochemical Modules**: Perform electrocoagulation, electro-oxidation, or electro-Fenton reactions, removing suspended solids and oxidizing persistent pollutants (Martínez-Huitle & Ferro, 2006).
- **Adsorption Columns**: ncorporate low-cost, waste-derived adsorbents (e.g., biochar, red mud composites, activated carbon) to capture residual contaminants or recover metals (Mohan *et al*., 2014).

These modules may operate **independently** or **sequentially**, depending on influent characteristics and effluent targets.

4.2 Real-time Monitoring and Control

A distinguishing feature of reaction pods is the integration of **smart sensing and automation**:

- **pH and Redox Sensors:** Provide continuous chemical feedback essential for optimizing oxidation-reduction reactions.
- **IoT Connectivity and Data Analytics:** Enable remote monitoring, predictive maintenance, and adaptive process control.
- **Artificial Intelligence Algorithms:** Optimize treatment efficiency by adjusting flow rates, reagent dosing, and energy input in real time (Zhang *et al*., 2021).

These capabilities ensure stable performance even under fluctuating wastewater loads.

4.3 Advantages of Decentralized Deployment

- **Flexibility:** Rapid installation and reconfiguration according to site-specific requirements.
- **Scalability:** Capacity can be expanded by adding more modules, without overhauling existing infrastructure.
- **Cost-effectiveness:** Reduces transportation and dependence on centralized treatment plants.

- **Sustainability:** Supports integration with renewable power sources and valorized catalysts.

These features make reaction pods particularly suitable for **small-to-medium industries, remote operations, and variable waste streams** where centralized treatment is impractical (Gikas & Tchobanoglous, 2009).

5. Green Solvent-Based and Hybrid Chemico-Biological Processes

Traditional solvent extraction methods for pollutant removal and resource recovery often rely on volatile organic solvents (VOCs) that pose risks to human health and the environment. In contrast, **green solvent systems** and **chemico-biological hybrids** represent sustainable alternatives that combine high selectivity with eco-compatibility, aligning with circular economy goals.

5.1 Green Solvent Technologies

- **Deep Eutectic Solvents (DESs):** DESs are mixtures of hydrogen-bond donors and acceptors that form low-volatility, tunable solvents. They are biodegradable, inexpensive, and effective for extracting metals, dyes, and organic contaminants from industrial effluents. Acidic DESs (e.g., choline chloride + oxalic acid) have shown high efficiency in recovering Pb, Zn, and Cr from wastewater and electronic waste (Smith *et al*., 2014; Abbott *et al*., 2017).

- **Ionic Liquids (ILs):** Although less biodegradable, ILs are highly stable and tunable, enabling selective removal of pharmaceuticals, dyes, and heavy metals. Their recyclability and low vapor pressure make them promising for closed-loop treatment systems (Zhu *et al*., 2016).

- **Supercritical Fluids (SCFs):** Supercritical CO_2 is a non-toxic solvent widely applied in food and pharmaceutical industries, with emerging applications in organic pollutant removal. Its low critical temperature and pressure allow efficient extraction while minimizing solvent residues (Brunner, 2005).

These solvents reduce secondary waste generation and can be reused, lowering both economic and environmental costs.

5.2 Chemico-Biological Hybrid Systems

Integrating chemical oxidation with biological treatment enhances pollutant removal by exploiting complementary strengths:

- **Sequential Reactors:** Chemical pre-treatment (e.g., ozonation, Fenton) degrades recalcitrant organics into biodegradable intermediates, which are then mineralized in biological reactors (Sarria *et al*., 2003).

- **Bioelectrochemical Systems (BESs):** Combine microbial metabolism with electrochemical processes, enabling simultaneous wastewater treatment and energy recovery in the form of hydrogen or electricity (Logan & Rabaey, 2012).

- **Enzyme-Assisted Treatments:** Enzymes such as laccases and peroxidases catalyze targeted reactions in complex effluents, often integrated with AOPs for enhanced selectivity and reduced energy input (Couto & Toca-Herrera, 2006).

5.3 Relevance to Industrial Applications

- **Textile Wastewater:** DES-based dye recovery and ozonation-biological hybrids have reduced color and toxicity with improved water reuse potential.

- **Pharmaceutical Effluents:** IL-based extractions coupled with enzyme-assisted treatments have shown promising results for removing antibiotics and endocrine disruptors.

- **Petrochemical Wastewater:** Hybrid oxidation-bioreactor systems achieve high COD removal (>90%), addressing refractory hydrocarbons.

These approaches demonstrate how **green chemistry principles** and **bio-integration** can transform industrial wastewater into a sustainable resource stream.

Table 2. Comparative overview of green solvent-based and hybrid chemico-biological processes for industrial wastewater treatment

Approach	Sub-type	Mechanism	Target Pollutants	Advantages	Limitation	Typical Applications
Green Solvents	Deep Eutectic Solvents (DESs)	Hydrogen-bond donor/acceptor complexes solubilize metals/dyes	Heavy metals (Pb, Cr, Zn), textile dyes	Low-cost, biodegradable, tunable	Limited large-scale data; viscosity issues	Metal recovery from plating/e-waste; dye removal
	Ionic Liquids (ILs)	Tunable ionic media extract	Pharmaceuticals, dyes, metals	High stability, reusable,	Costly, low biodegradability	Pharmaceutic-al and specialty chemical

		metals and organics		selective		wastewater
	Supercritical Fluids (SCFs, esp. CO_2)	Solubilization of organics under supercritical conditions	Hydrocarbons, pharmaceuticals	Non-toxic, residue-free, reusable	High-pressure equipment; energy intensive	Petrochemical & pharma wastewater
Hybrid Systems	Sequential Reactors (Chemical + Biological)	Pre-oxidation breaks down recalcitrants → biodegradation	Dyes, phenols, hydrocarbons	High COD reduction, improved biodegradability	Two-step process; higher footprint	Textile, petrochemical effluents
	Bioelectrochemical Systems (BESs)	Microbial metabolism + electrochemistry	Organics, nutrients	Simultaneous treatment + energy recovery (H_2/electricity)	Scaling & electrode cost	Institutional & food industry wastewater
	Enzyme-Assisted Processes	Oxidative enzymes (laccases, peroxidases) degrade specific pollutants	Phenols, dyes, pharmaceuticals	High selectivity, mild conditions	Enzyme cost, stability issues	Dyeing, pharmaceutical effluents

Critical Insights

While green solvent-based and hybrid chemico-biological systems offer significant promise for sustainable wastewater management, their transition from laboratory research to industrial deployment faces notable challenges. For instance, although DESs are low-cost and biodegradable, their relatively high viscosity and limited recyclability can hinder large-scale application (Smith *et al*., 2014). Similarly, ionic liquids offer high selectivity but suffer from low biodegradability and cost barriers, restricting use outside niche industries (Zhu *et al*., 2016). Supercritical fluids, while effective and residue-free, require high-pressure equipment and energy-intensive conditions that may offset their environmental benefits (Brunner, 2005).

Hybrid systems also face operational bottlenecks. Enzyme-assisted treatments are highly selective but limited by enzyme stability, activity in complex matrices, and production costs (Couto & Toca-Herrera, 2006). Bioelectrochemical systems offer the dual benefit of pollutant removal and energy recovery, but scaling them up remains a significant hurdle due to electrode material costs and biofilm management (Logan & Rabaey, 2012). Sequential chemical-biological processes, though effective, often demand larger footprints and complex operational control (Sarria *et al*., 2003).

These limitations suggest that while Table 2 highlights a diverse portfolio of promising solutions, their practical viability depends on coupling with digital tools and adaptive control strategies. Real-time monitoring, IoT integration, and AI-assisted optimization could help overcome process inefficiencies, stabilize performance under variable conditions, and accelerate industrial adoption. This convergence of green chemistry with smart technologies forms the focus of Section 6.

6. Real-World Applications and Case Studies

The transition from laboratory-scale research to industrial-scale deployment remains the ultimate test for advanced wastewater treatment strategies. Real-world case studies highlight both the opportunities and challenges associated with implementing circular, modular, and hybrid approaches in diverse sectors.

6.1 Textile Industry

The textile sector produces highly colored effluents containing dyes, surfactants, and heavy metals.

- **Hybrid Treatment:** A full-scale textile plant in Spain demonstrated the use of ozonation as a pre-treatment followed by biological reactors, achieving >90% COD and >95% color removal (Sarria *et al*., 2003).
- **Green Solvent Integration:** Pilot studies in India have tested DES-based dye recovery from effluents, enabling solvent recyclability and potential dye reuse (Smith *et al*., 2014).

6.2 Pharmaceutical and Chemical Industry

Pharmaceutical wastewater contains a complex mixture of antibiotics, endocrine disruptors, and solvents that are often resistant to conventional biological treatment.

- **Electrochemical Systems:** In Switzerland, electro-Fenton systems have been deployed for antibiotic degradation at pilot scale, with >80% removal efficiency for ciprofloxacin and related compounds (Martínez-Huitle & Ferro, 2006).

- **Ionic Liquids:** Case studies in China show IL-based extraction for separating pharmaceutical intermediates from effluents, with closed-loop solvent recovery reducing VOC emissions (Zhu *et al*., 2016).

6.3 Petrochemical Industry

Petrochemical plants generate wastewater containing refractory hydrocarbons, phenols, and complex organics.

- **Supercritical Fluids:** Supercritical CO_2 extraction has been piloted in Germany for hydrocarbon separation from refinery wastewater, demonstrating >70% removal efficiency while enabling hydrocarbon recovery (Brunner, 2005).

- **Modular Pods**: Containerized electrochemical–adsorption pods have been trialed in the Middle East for refinery effluents, reducing COD by 65–75% while allowing rapid deployment and relocation (Gikas & Tchobanoglous, 2009).

6.4 Food and Beverage Industry

High-strength effluents from distilleries, dairies, and food-processing plants are rich in organics and nutrients.

- **Bioelectrochemical Systems:** Microbial fuel cells have been tested in brewery wastewater treatment, simultaneously reducing COD by ~85% and generating small but useful amounts of electricity (Logan & Rabaey, 2012).

- **Enzyme-Assisted Systems:** Pilot trials in dairy effluents have shown laccase-based treatment effective in reducing phenolic content by ~70% (Couto & Toca-Herrera, 2006).

6.5 Key Lessons from Industrial Adoption

- **Scalability:** Modular and hybrid systems show promise, but scaling remains limited by cost, energy input, and maintenance requirements.

- **Integration:** Case studies highlight that no single process suffices; **sequential or combined methods** consistently outperform stand-alone technologies.

- **Circularity:** Resource recovery (e.g., dyes, metals, hydrocarbons, clean water) is feasible, but requires clear economic incentives and regulatory support.

- **Digital Tools:** Deployment success often hinges on real-time monitoring and adaptive control, suggesting that the **integration of IoT and digital twins** will be essential for next-generation systems.

7. Digital Twins and Industry–Academia Collaborations for Scaling and Optimization

The real-world scalability of advanced wastewater treatment technologies is limited not only by technical challenges but also by economic feasibility, policy frameworks, and operational adaptability. To overcome these barriers, **digital twin technologies** and **strategic collaborations between industry and academia** are emerging as critical enablers of system optimization, scale-up, and long-term sustainability.

7.1 Digital Twins for Wastewater Systems

A **digital twin** is a virtual replica of a physical system that integrates real-time data, predictive modeling, and feedback control to optimize operations (Tao *et al*., 2018). In wastewater treatment, digital twins can:

- **Monitor & Predict:** Continuously analyze influent quality, energy demand, and reaction performance.

- **Optimize Processes:** Enable adaptive dosing of reagents, energy-efficient operation of electrochemical and photochemical modules, and predictive maintenance of equipment.

- **Scenario Testing:** Simulate "what-if" scenarios (e.g., sudden pollutant spikes, energy fluctuations) without disrupting actual operations.

- **Integration with IoT:** Deploy smart sensors (pH, ORP, flow, COD) to feed into AI-driven optimization algorithms (Zhang *et al*., 2021).

Case studies in Europe and East Asia demonstrate that digital twins applied to municipal and industrial wastewater plants can reduce energy use by up to 15–20% and enhance treatment efficiency by 10–15% (Corominas *et al*., 2020).

7.2 Industry–Academia Collaborations

Bridging the gap between **laboratory-scale research** and **industrial-scale implementation** requires collaborative frameworks that pool expertise, infrastructure, and financial resources.

- **Joint Pilot Projects:** Universities provide innovation (new catalysts, solvents, hybrid systems), while industries supply effluent samples and pilot-scale setups.

- **Knowledge Transfer:** Academia develops advanced modeling, AI algorithms, and sustainable treatment chemistries, while industries contribute operational know-how and cost analysis.

- **Funding Consortia:** Public-private partnerships and international funding (EU Horizon, Japan's NEDO, India's GCRF-equivalents) support translational projects that accelerate commercialization.

- **Training & Workforce Development:** Collaborations ensure skill transfer through training programs in digital water management, process modeling, and sustainability metrics (Howarth *et al*., 2020).

7.3 Towards Scalable and Adaptive Systems

For the advanced strategies outlined in this review (Sections 2–6) to move beyond pilot trials, scaling must involve both **technological integration** and **ecosystem collaboration**.

- Digital twins provide the **decision-support framework**, while industry–academia partnerships provide the **testing grounds and implementation pathways**.
- Together, these approaches ensure that modular pods, green solvents, and hybrid systems can evolve into **standardized, scalable, and economically viable solutions** for diverse industries.

Conclusion

Industrial liquid-waste management is undergoing a paradigm shift from conventional linear treatment models toward **circular, adaptive, and resource-recovering frameworks**. This review has highlighted how **advanced chemistries** (e.g., AOPs, electrochemical oxidation, green solvents) and **hybrid processes** (e.g., chemical–biological integration, enzyme-assisted systems, bioelectrochemical technologies) are redefining wastewater treatment as not merely a disposal necessity but a source of valuable resources.

The valorization of industrial by-products such as **red mud, sludge, and agricultural residues** into functional adsorbents and catalysts exemplifies the **waste-to-resource** transition that underpins the circular economy. At the same time, **modular reaction pods** and containerized systems offer scalable, site-specific solutions that can be rapidly deployed across industries with variable wastewater profiles. **Case studies** from textiles, pharmaceuticals, petrochemicals, and food processing illustrate the feasibility and limitations of these strategies, reinforcing the importance of **integration rather than stand-alone processes**.

Looking forward, **digital twins, IoT-enabled monitoring, and industry–academia collaborations** will be critical for bridging the gap between laboratory innovation and real-world application. By enabling predictive optimization, adaptive control, and workforce training, these frameworks provide the ecosystem necessary for **scaling advanced treatment strategies to global industry**.

Ultimately, achieving sustainable industrial wastewater management will require a **systems-level approach**—one that integrates advanced chemical processes, hybrid chemico-biological strategies, smart digital tools, and collaborative partnerships. Such an approach not only ensures regulatory compliance and cost-effectiveness but also aligns with global **Sustainable Development Goals (SDGs 6, 9, 12, 13)**, transforming wastewater into a driver of environmental and economic resilience.

Future Perspectives

While promising progress has been made in advanced chemical, hybrid, and modular wastewater treatment strategies, several frontiers remain critical for future research and deployment:

- **Integration of Digital Twins with Modular Pods:** Embedding real-time digital twins into decentralized “reaction pods” could enable adaptive, self-optimizing treatment systems suitable for fluctuating industrial loads.
- **Scalable Valorization Pathways:** Transforming industrial residues (red mud, sludge, biomass) into standardized, high-performance adsorbents and catalysts at scale remains a pressing challenge requiring techno-economic optimization.
- **Greener Solvents and Enzymes:** Future work should focus on developing biodegradable, recyclable solvents and more robust enzyme-based systems, reducing reliance on costly or toxic reagents.
- **Cross-Sector Collaborations:** Broader academia–industry–policy collaborations are needed to accelerate technology transfer, establish regulatory frameworks, and ensure economic incentives for resource recovery.
- **Sustainability Metrics and SDG Alignment:** Beyond technical performance, future assessments must incorporate life-cycle analysis, carbon footprint, and SDG-driven metrics to ensure holistic sustainability.

By advancing these directions, wastewater treatment can move decisively from end-of-pipe remediation toward a **resource-positive and climate-resilient industrial ecosystem**.

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