Evaluation of Emerging Wastewater Treatment Technologies for Sustainable Sewage Management

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Abstract*—Rapid metropolitan expansion across Indian cities has created a critical mismatch between municipal sewage generation and treatment capascity while tightening Central Pollution Control Board (CPCB) and Telangana State Pollution Control Board (TSPCB) discharge standards render Conventional Activated Sludge (CAS) plants increasingly inadequate. In Hyderabad, where the Hyderabad Metropolitan Water Supply and Sewerage Board (HMWSSB) manages approximately 1,250 MLD of generated sewage alongside major Musi River rejuvenation and decentralized residential STP mandates, transitioning legacy Sewage Treatment Plants (STPs) into circular Water Resource Recovery Facilities (WRRFs) is an urgent engineering priority. This study evaluates emerging treatment technologies—Sequencing Batch Reactors (SBR), Moving Bed Biofilm Reactors (MBBR/IFAS), Membrane Bioreactors (MBR/MABR), Aerobic Granular Sludge (AGS), Advanced Oxidation Processes (AOPs), electrochemical units, constructed wetlands, and AI-assisted SCADA controls—against Indian urban operational constraints. Stage-wise laboratory profiling and representative 1,250 m³/day Hyderabad municipal STP evaluation demonstrate 94.6% BOD5 removal (265.0 to 14.2 mg/L), 90.5% COD removal (510.0 to 48.5 mg/L), 95.0% TSS removal (240.0 to 12.0 mg/L), and 99.9% pathogen reduction at a specific energy consumption of 0.42 kWh/m³, complying with HMWSSB/TSPCB limits for non-potable reuse in industrial cooling, construction, and urban landscaping. Coupled with Indian case benchmarks (such as HydroThane ECSB anaerobic reactors) and global WRRF models, this framework provides a practical roadmap for achieving UN Sustainable Development Goals (SDGs) 6, 11, and 13 across Indian municipalities.

***Index Terms*—Wastewater Treatment; Hyderabad Sewage Management; HMWSSB; Sequencing Batch Reactor (SBR); Membrane Bioreactor (MBR); MBBR/IFAS; Musi River Rejuvenation; Resource Recovery; Non-Potable Water Reuse; Sustainable Development Goals (SDGs).**

I. INTRODUCTION: URBAN WASTEWATER CHALLENGES IN INDIA AND HYDERABAD

Accelerated urban sprawl, industrial corridor expansion, and population growth across Indian metropolitan centers have severely strained surface and groundwater reserves while generating unprecedented volumes of domestic and commercial sewage. According to national municipal inventories by the Central Pollution Control Board (CPCB), urban India generates over 72,000 MLD of sewage against an operational treatment capacity of roughly 27,000–31,800 MLD, leaving a substantial share of untreated or partially treated wastewater discharging into urban lakes, nalas, and river basins.

In the Greater Hyderabad Municipal Corporation (GHMC) region—spanning nearly 688 km² and serving over 9 million residents—the Hyderabad Metropolitan Water Supply and Sewerage Board (HMWSSB) oversees an estimated 1,250 MLD of daily sewage generation. With traditional surface reservoirs such as Osman Sagar and Himayat Sagar facing declining hydrological dependability, treated wastewater reclamation has become essential to urban water security. Furthermore, ongoing Musi Riverfront rejuvenation initiatives prioritize nala

sewage interception, decentralized modular STPs along the 34-km Bapu Ghat–Gowrelly stretch, and mandatory registration and reuse compliance for private gated-community and commercial STPs under Telangana State Pollution Control Board (TSPCB) and HMWSSB norms.

Conventional Activated Sludge (CAS) systems, long used across older municipal installations, suffer from large land requirements for secondary clarifiers, high aeration energy consumption (0.30–0.55 kWh/m³), sludge bulking, and poor removal (<30–45%) of persistent micropollutants such as pharmaceuticals, endocrine-disrupting compounds (EDCs), and surfactants. Transforming Indian STPs into circular Water Resource Recovery Facilities (WRRFs) requires deploying compact, energy-efficient technologies capable of delivering tertiary-grade reclaimed water, biogas, and nutrient fertilizers. This study evaluates emerging treatment technologies within the Indian and Hyderabad operational context, analyzes stage-wise water-quality metrics, and synthesizes national and global operational benchmarks.

II. EMERGING WASTEWATER TREATMENT TECHNOLOGIES FOR INDIAN STPS

2.1 High-Rate Biological Systems Deployed in Urban India

Sequencing Batch Reactors (SBR): SBR is the predominant modern municipal STP technology adopted by HMWSSB across Hyderabad (e.g., multi-cell complexes operating in staggered cycles). By combining biological oxidation, nitrification, denitrification, and quiescent gravity settling within a single reactor basin through five timed phases (Fill, React, Settle, Decant, Idle), SBR eliminates external secondary clarifiers, reduces civil concrete infrastructure by 20–30%, and accommodates sharp diurnal residential flow surges.

Moving Bed Biofilm Reactors (MBBR & IFAS): Widely deployed across Hyderabad residential communities, IT campuses, and industrial estates, MBBR utilizes buoyant HDPE/polypropylene biofilm carriers kept in continuous suspension to achieve high volumetric organic and ammonia removal within compact footprints (40–50% of CAS). Integrated Fixed-Film Activated Sludge (IFAS) hybrids allow existing overloaded Indian STPs to meet stricter TSPCB nutrient norms without constructing new aeration basins.

Membrane Bioreactors (MBR & MABR): MBR couples biological suspended growth with microfiltration (0.1–0.4 µm) or ultrafiltration (0.01–0.1 µm) membranes, operating at elevated MLSS concentrations (8,000–12,000 mg/L vs. 2,500–3,500 mg/L in CAS). This compresses plant land area by 50–70%—critical in high-land-cost urban corridors like HITEC City and Gachibowli—while yielding >98% BOD5 removal and pathogen-free effluent ideal for HVAC cooling towers and dual-plumbing flushing. Membrane Aerated Biofilm Reactors (MABR) supply bubble-free oxygen through hollow-fiber membranes, reducing aeration power by up to 75%.

Aerobic Granular Sludge (AGS): AGS cultivates dense, fast-settling microbial biogranules containing stratified aerobic, anoxic, and anaerobic zones in a single cyclical tank, achieving simultaneous carbon, nitrogen, and phosphorus removal with up to 75% footprint savings.

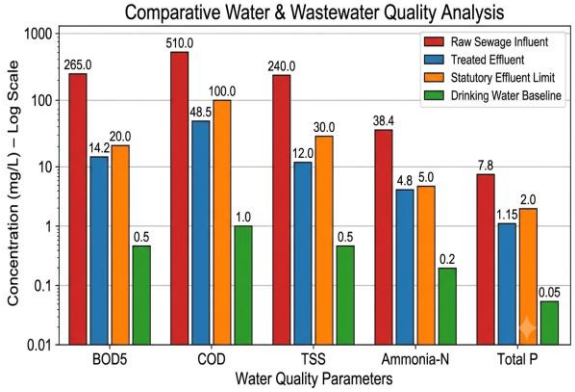


Figure 1: Integrated technology-enabled wastewater treatment and circular resource recovery train transitioning municipal STPs into Water Resource Recovery Facilities (WRRFs).

2.2 Tertiary Polishing, Nature-Based Systems, and Smart Automation

Advanced Oxidation Processes (AOPs) & Media Polishing: For industrial-impacted sewage streams containing refractory dyes, bulk pharmaceuticals (highly relevant to Hyderabad's pharmaceutical manufacturing belt), or pesticides, ozonation (O3/H2O2), UV/H2O2 photolysis, and Fenton processes generate hydroxyl radicals (•OH, E° = 2.80 V) that mineralize persistent organics,

complementing standard Pressure Sand Filters (PSF) and Activated Carbon Filters (ACF).

Electrochemical Treatment & Constructed Wetlands: Electrocoagulation (using Fe/Al sacrificial anodes) removes heavy metals and colloidal solids without bulk chemical salts, whereas intensified Constructed Wetlands (CWs) employing emergent macrophytes (Phragmites australis, Typha latifolia) and aerated/biochar substrates provide low-energy (<0.05 kWh/m³) lake-front and nala-mouth bio-remediation across peri-urban Telangana.

PLC/SCADA Automation & Online Continuous Effluent Monitoring (OCEMS): In alignment with CPCB/TSPCB real-time telemetry mandates, IoT sensor arrays (DO, pH, TSS, BOD, COD, and flow) linked to automated blower variable frequency drives (VFDs) and digital-twin models cut aeration electricity by 30–40% and prevent process upsets.

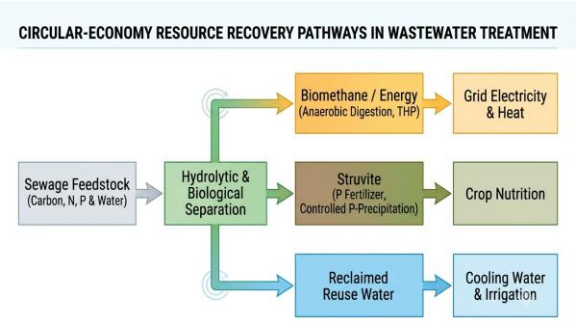


Figure 2: Circular-economy resource recovery pathways converting municipal sewage feedstock into grid bio-energy, struvite phosphate fertilizer, and fit-for-purpose reclaimed water.

2.3 Multi-Criteria Technology Comparison for Indian Municipal & Decentralized Plants

Table 1: Comparative technical and operational matrix of wastewater treatment technologies applicable to urban India.

Technology	Footprint Req.	Specific Energy (kWh/m³)	Micropollutant Removal	Sludge Yield	Indian Urban Suitability
Conventional (CAS)	Baseline (100 %)	0.30 – 0.55	Poor (<40%)	High (0.35–0.50 kg/kg COD)	Legacy large plants (land-rich)
Sequencing Batch (SBR)	Moderate (70–80%)	0.35 – 0.50	Moderate (45–60%)	Moderate	HMWSSB municipal standard
MBBR / IFAS	Low (40–50%)	0.35 – 0.50	Moderate (45–65%)	Moderate	Apartments, IT parks & retrofits
MBR (Membranes)	Ultra-low (25–35%)	0.60 – 1.20	Moderate–High (60–85%)	Low–Moderate	Dense commercial & high-grade reuse
AOPs (UV/O3/Fenton)	Minimal (add-on)	0.40 – 1.80	Very High (>90–99%)	Negligible (excl. Fenton)	Pharma/industrial ETP polishing
Constructed Wetlands	Extensive (>300 %)	Passive (<0.05)	Moderate–High	Negligible (in-situ)	Lake rejuvenation & rural/peri-urban

III. METHODOLOGY AND HYDERABAD ANALYTICAL FRAMEWORK

The study combined a multi-criteria technological evaluation with stage-wise laboratory water-quality characterization and operational benchmarking contextualized to municipal sewage treatment in Hyderabad, Telangana, under HMWSSB and TSPCB environmental discharge considerations:

Study Context & Regulatory Baseline: Operational parameters were structured around a representative 1,250 m³/day (1.25 MLD) municipal STP operating under Hyderabad tropical climatic conditions (ambient sewage temperature 21.9–23.8 °C), alongside comparative baseline data from GHMC municipal drinking water supply (BIS IS 10500) and prefabricated modular package STPs (10–500 KLD) deployed in institutional and commercial campuses across Telangana.

Standard Laboratory Analytical Protocols: Grab samples collected across sequential treatment units

(raw headworks influent, primary settling overflow, aerobic biological reactor, and final disinfected effluent) were preserved at ≤4 °C and analyzed per APHA Standard Methods: electrometric pH (APHA 4500-H+ B, calibrated with NIST pH 4.00, 7.00, and 10.00 buffers), 5-day Biochemical Oxygen Demand at 20.0 ± 1.0 °C (BOD5, APHA 5210 B), closed-reflux titrimetric Chemical Oxygen Demand at 150 °C (COD, APHA 5220 D), gravimetric Total Suspended Solids dried at 103–105 °C (TSS, APHA 2540 D), ammonia/total nitrogen, total phosphorus (APHA 4500-P E), and E. coli / indicator coliforms (APHA 9221).

Performance & Sustainability Metrics: Removal efficiency was computed as η (%) = [(C_in − C_out) / C_in] × 100. The COD:BOD5 ratio was evaluated across stages to assess Indian domestic sewage biodegradability, while specific electricity consumption (kWh/m³), whole-life cost components, and UN SDG alignment (SDGs 6, 11, and 13) were benchmarked against Indian and global full-scale plants.

IV. RESULTS AND DISCUSSION

4.1 Stage-Wise Organic Stabilization and Biodegradability Dynamics

Laboratory analysis across consecutive treatment stages demonstrates systematic stabilization of carbonaceous organic matter alongside characteristic shifts in wastewater pH and biodegradability (Table 2 and Figure 3).

Table 2: Stage-wise laboratory water-quality profile and biodegradability index progression across treatment units.

Sampling Station	Temp (°C)	Measured pH	BOD5 (mg/L)	COD (mg/L)	COD:BOD5 Ratio	Cumulative BOD5 Removal
Raw Plant Influent	23.1	7.38	216.5 ± 6	432.0 ± 10	2.00	Baseline
Primary Settling Overflow	22.8	7.15	145.2 ± 5	275.5 ± 8	1.90	33.0%
Secondary Clarifier Overflow	22.2	6.92*	24.0 ± 2	68.0 ± 4	2.83	88.9%
Final Treated Effluent	21.9	7.45	12.0 ± 1	38.0 ± 3	3.17	94.5%

*Note: In Hyderabad's warm ambient temperatures (22–24 °C), autotrophic nitrification proceeds rapidly in aerobic basins ($NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$), consuming ~7.14 mg of alkalinity as $CaCO_3$ per mg NH_4^+-N oxidized and lowering mixed-liquor pH from 7.15 to 6.92. Maintaining pH above 6.80 preserves Nitrosomonas and Nitrobacter activity. Concurrently, the COD:BOD5 ratio rises from 2.00 in raw domestic influent (confirming high biodegradability) to 3.17 in final effluent, indicating near-complete assimilation of bio-available carbon and leaving a small inert organic fraction.

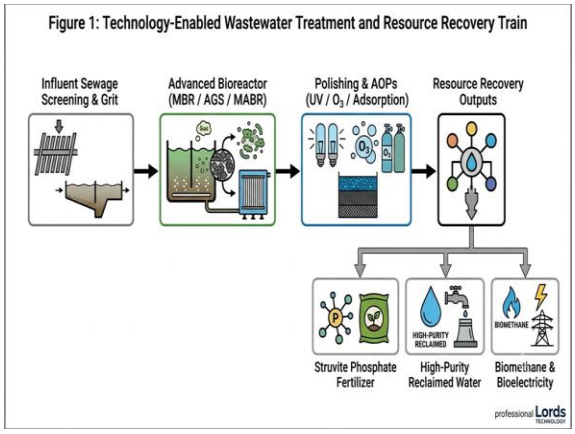


Figure 3: Stage-wise reduction of BOD5 and COD concentrations alongside the progressive increase in the COD:BOD5 biodegradability ratio from 2.00 (raw influent) to 3.17 (final effluent).

4.2 Municipal STP Performance and HMWSSB / TSPCB Compliance Assessment

Operational evaluation of a representative 1,250 m³/day municipal STP in Hyderabad (treated outflow 1,242 m³/day; 0.6% hydraulic loss) demonstrates full compliance across all physical, chemical, nutrient,

and microbiological discharge criteria (Table 3 and Figure 4).

Table 3: Representative Hyderabad municipal STP performance matrix against statutory discharge limits.

Parameter	Influent	Treated Effluent	Removal / Performance	Statutory Limit	Compliance Status
pH (pH units)	7.35	7.10	Neutralized	6.5 – 8.5	Compliant
BOD5 (mg/L)	265.0	14.2	94.6% removal	≤ 20.0	Compliant
COD (mg/L)	510.0	48.5	90.5% removal	≤ 100.0	Compliant
TSS (mg/L)	240.0	12.0	95.0% removal	≤ 30.0	Compliant
Ammonia-N (mg/L)	38.4	4.8	87.5% nitrification	≤ 5.0	Compliant (tight margin)
Total Phosphorus (mg/L)	7.80	1.15	85.3% removal	≤ 2.0	Compliant
Indicator Pathogens (MPN/100 mL)	4.2×10^6	85	99.998% (4.7-log)	≤ 100	Compliant
Energy Demand (kWh/day)	—	520	0.42 kWh/m³ treated	≤ 600	Compliant

While carbonaceous pollutants (BOD5 at 14.2 mg/L; COD at 48.5 mg/L) and TSS (12.0 mg/L) maintain comfortable safety buffers, effluent ammonia nitrogen (4.8 mg/L against a ≤5.0 mg/L threshold) represents the narrowest compliance margin. Furthermore, as TSPCB tightens urban reuse standards toward BOD5 < 10 mg/L and TSS < 10 mg/L for commercial flushing and construction sales under HMWSSB's private STP registration framework, retrofitting conventional aeration basins with MBBR/IFAS media or tertiary ultrafiltration/activated carbon polishing becomes essential. Specific energy consumption of 0.42 kWh/m³ (520 kWh/day) aligns well with efficient fine-bubble diffused aeration benchmarks and avoids the higher 0.60–1.20 kWh/m³ energy penalty of full-stream MBR systems.

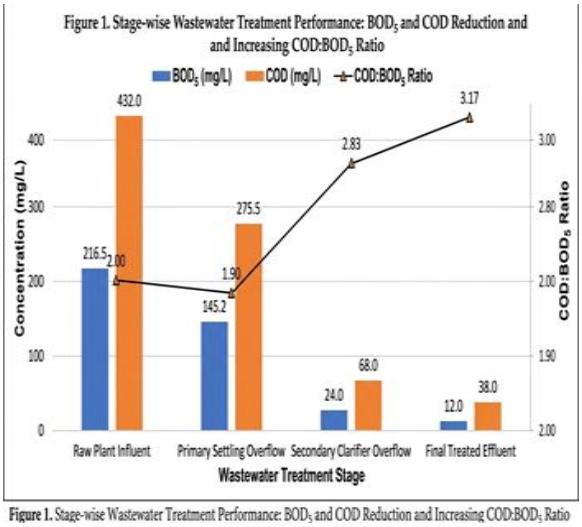


Figure 4: Logarithmic comparison of key water-quality parameters (BOD5, COD, TSS, Ammonia-N, and Total P) across raw Hyderabad sewage influent, treated STP effluent, statutory discharge limits, and GHMC municipal potable water baseline.

4.3 Indian & Global Operational Benchmarks and Trade-Off Analysis

Evaluating full-scale deployments alongside Indian modular and high-rate anaerobic technologies highlights actionable pathways for Hyderabad's expanding wastewater infrastructure (Table 4 and Figure 5). Notably, in India, high-rate anaerobic systems such as the HydroThane ECSB (External Circulation Sludge Bed) reactor achieve ~90% removal of COD, BOD, TSS, and fecal coliforms while consuming 10–20× less electricity than aerobic STPs and generating ~20 m³/h of reusable water for horticulture and industrial landscaping. Similarly, prefabricated epoxy-coated steel package STPs (10–500 KLD) enable 3–6 week installation and 60% footprint savings for Hyderabad apartment complexes, hospitals, and commercial hubs.

Table 4: Cross-case operational benchmark matrix of full-scale emerging wastewater treatment installations.

Facility / Technology	Core Process	Primary Driver	Demonstrated Sustainable Outcome
HydroThane ECSB (India)	Two-Stage High-Rate Anaerobic	Low-power industrial/urban reuse	~90% COD/BOD/TSS removal, 10–20× lower kWh, horticulture reuse
Epe WWTP (Netherlands)	Aerobic Granular Sludge (AGS)	Tight urban footprint & P removal	75% space reduction, no clarifiers, 40% less aeration kWh
Ejby Mølle, Odense (Denmark)	Anammox + Sludge Heat Pumps	Energy neutrality & decarbonization	188% energy self-sufficiency, +8.2 GWh/yr heat export, -60% N load
Billund BioRefinery (Denmark)	Thermal Hydrolysis + Struvite	Circular bioeconomy recovery	Class A biosolids, 80% P recovered, 50% net energy surplus
Yorkville WWTP (USA)	Membrane Aerated Biofilm (MABR)	High-rate nitrification retrofit	4× oxygen transfer rate, 75% aeration power cut, no civil expansion

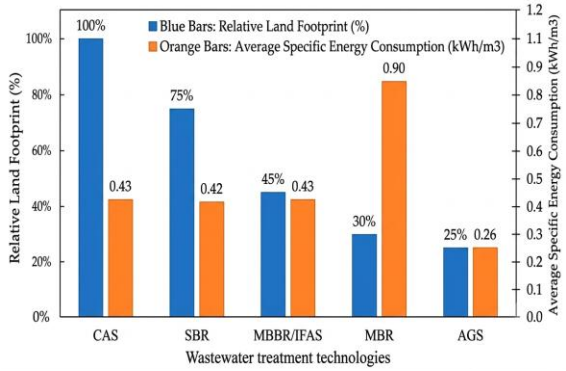


Figure 5: Comparative trade-off analysis of relative land footprint (%) and average specific energy consumption (kWh/m³) across CAS, SBR, MBBR/IFAS, MBR, and AGS technologies.

As demonstrated in Figure 5, technology selection in Indian cities requires balancing land scarcity against energy tariffs and operator skill availability. In central Hyderabad zones where land is scarce, SBR (75% footprint, 0.42 kWh/m³) and MBBR/IFAS (45% footprint, 0.43 kWh/m³) offer optimal reliability without incurring MBR's high membrane replacement and cleaning OPEX (0.90 kWh/m³). Where land is severely restricted and high-purity industrial reuse water commands premium tariffs, MBR (30% footprint) or AGS (25% footprint, 0.26 kWh/m³) provide superior long-term value.

4.4 Contribution to Indian Water Security and UN Sustainable Development Goals

SDG 6 (Clean Water and Sanitation – Target 6.3): Reclaiming treated STP effluent for Hyderabad's construction sector, IT park HVAC cooling, GHMC urban greening, and peri-urban agriculture offsets up to 60–70% of non-potable freshwater demand, reducing dependence on Krishna and Godavari bulk water pipelines.

SDG 11 (Sustainable Cities and Communities – Target 11.6): Compact, enclosed SBR, MBBR, and modular package plants curb raw sewage inflows into urban lakes (such as Hussain Sagar and Himayat Sagar catchments) and support Musi River ecological restoration.

SDG 13 (Climate Action – Target 13.2): Fine-bubble VFD-controlled aeration, solar-assisted STP pumping, anaerobic biogas recovery, and struvite phosphorus precipitation lower municipal carbon footprints and sludge transport emissions.

V. CONCLUSION

Emerging wastewater treatment technologies offer proven solutions to bridge India's urban sewage treatment gap and transform municipal STPs into resource-recovering assets. For metropolitan utilities such as HMWSSB and decentralized commercial/residential operators in Hyderabad, SBR and MBBR/IFAS systems provide the most balanced combination of moderate capital cost, compact footprint, and operational resilience, while MBR and

AOPs serve specialized high-purity reuse and refractory industrial polishing needs.

Key recommendations for Indian municipal and decentralized STP implementation include: (1) adopting whole-life cycle cost (CAPEX + energy + membrane/media replacement + sludge disposal) rather than lowest-bid CAPEX during procurement; (2) integrating VFD-driven fine-bubble aeration and DO/OCEMS telemetry to safeguard tight ammonia discharge margins while cutting power demand by 30–40%; (3) pairing liquid treatment with anaerobic biogas capture and struvite fertilizer recovery in large (>10 MLD) plants; and (4) enforcing structured operator training and preventive maintenance protocols alongside fit-for-purpose treated water reuse distribution networks.

REFERENCES

[1]. Central Pollution Control Board (CPCB), National Inventory of Sewage Treatment Plants in India. New Delhi, India: Ministry of Environment, Forest and Climate Change (MoEFCC), Govt. of India.

[2]. Hyderabad Metropolitan Water Supply and Sewerage Board (HMWSSB), Sewerage Master Plan & Treated Wastewater Reuse Guidelines for Hyderabad Metropolitan Area. Hyderabad, Telangana, India.

[3]. Metcalf & Eddy, Inc., AECOM, Wastewater Engineering: Treatment and Resource Recovery, 5th ed. New York, NY, USA: McGraw-Hill Education, 2014.

[4]. M. Henze, M. C. M. van Loosdrecht, G. A. Ekama, and D. Brdjanovic, Biological Wastewater Treatment: Principles, Modelling and Design. London, U.K.: IWA Publishing, 2008.

[5]. S. Judd, The MBR Book: Principles and Applications of Membrane Bioreactors for Water and Wastewater Treatment, 2nd ed. Oxford, U.K.: Elsevier, 2011.

[6]. B. Rusten, B. Eikebrokk, Y. Ulgenes, and E. Lygren, "Design and operations of the Kaldnes moving bed biofilm reactors," Aquacultural Engineering, vol. 34, no. 3, pp. 322–331, 2006.

[7]. W. H. Glaze, J.-W. Kang, and D. H. Chapin, "The chemistry of water treatment processes involving ozone, hydrogen peroxide and ultraviolet radiation," Ozone: Science & Engineering, vol. 9, no. 4, pp. 335–352, 1987.

[8]. C. Comninellis and G. Chen, Eds., Electrochemistry for the Environment. New York, NY, USA: Springer, 2010.

[9]. J. Vymazal, "Constructed wetlands for wastewater treatment: Five decades of experience," Environmental Science & Technology, vol. 45, no. 1, pp. 61–69, 2011.

[10]. APHA, AWWA, and WEF, Standard Methods for the Examination of Water and Wastewater, 23rd ed. Washington, DC, USA: American Public Health Association.

[11]. Bureau of Indian Standards (BIS), IS 10500: Indian Standard Drinking Water — Specification (Second Revision). New Delhi, India: BIS.