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Wastewater Treatment and Reuse Technologies

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ABSTRACT

Freshwater scarcity, population growth, rapid urbanization, and the escalating discharge of inadequately treated wastewater into rivers, lakes, and coastal waters are converging into one of the most serious environmental and public health challenges of the twenty-first century. Wastewater — the spent water from domestic, commercial, industrial, and agricultural activities — contains a complex mixture of organic matter, nutrients, suspended solids, pathogens, heavy metals, and emerging contaminants including pharmaceuticals and microplastics that pose severe risks to human health and aquatic ecosystems when discharged without adequate treatment. This article presents a comprehensive review of wastewater treatment and reuse technologies, systematically covering the characteristics and composition of municipal and industrial wastewater, the unit processes of primary, secondary, and tertiary treatment, advanced treatment technologies for reuse applications including membrane bioreactors, reverse osmosis, ultraviolet disinfection, advanced oxidation processes, and constructed wetlands, and the principal reuse categories of agricultural irrigation, industrial process water, groundwater recharge, and indirect and direct potable reuse. Comparative performance data are presented across treatment technologies and reuse quality standards. Case studies from Singapore's NEWater program, Israel's Shafdan plant, India's Nagpur and Surat treatment facilities, and Namibia's Windhoek direct potable reuse scheme illustrate the spectrum of global practice. The regulatory frameworks of India, the European Union, the United States, and WHO are reviewed, and the environmental, economic, and social dimensions of wastewater reuse are analyzed. Challenges including emerging contaminants, sludge management, energy consumption, and public acceptance are examined alongside future research directions including resource recovery, energy-neutral treatment, and the circular water economy.

Keywords: wastewater treatment, water reuse, membrane bioreactor, reverse osmosis, activated sludge, constructed wetlands, potable reuse, NEWater, advanced oxidation, nutrient recovery, emerging contaminants, circular water economy

1. Introduction

Water is not merely a resource — it is the medium through which human metabolism, food production, industrial activity, and ecosystem function are sustained. Yet the global freshwater system is under extraordinary and accelerating stress. According to the United Nations World Water Development Report 2023, approximately 2.4 billion people live in water-stressed countries, global water demand has increased six-fold over the past 100 years and continues to grow at roughly 1 percent per year, and climate change is intensifying the hydrological cycle in ways that increase both the frequency of droughts and the intensity of floods while reducing the reliability of snowpack and glacier-fed river systems that billions depend upon.

Against this backdrop of scarcity, the world generates and largely wastes an enormous volume of water that has already been collected, conveyed, and used — wastewater. Global municipal wastewater generation is estimated at over 380 billion cubic meters per year, of which fewer than 56 percent receives any form of treatment before discharge, according to the UN Environment Programme. In India, the Central Pollution Control Board estimates that urban areas generate approximately 72,368 million liters per day (MLD) of wastewater, against installed treatment capacity of only 31,841 MLD — a treatment gap of nearly 56 percent — and actual treatment of considerably less, as many installed plants operate below design capacity due to inadequate power supply, poor maintenance, and hydraulic underloading. The consequence is the discharge of billions of liters of raw or partially treated sewage daily into India's rivers, degrading the ecological condition

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of iconic water bodies including the Yamuna, Ganga, and Sabarmati despite decades of remediation investment.

The framing of wastewater as a waste product to be disposed of is fundamentally misconceived. Treated wastewater is a reliable, weather-independent source of water that can substitute for increasingly scarce freshwater in a wide range of applications. It contains nutrients — nitrogen, phosphorus, potassium — that are valuable fertilizers recoverable through appropriate treatment processes. It contains organic matter that can be converted to biogas energy through anaerobic digestion. It contains thermal energy exploitable through heat pumps. And it contains, increasingly, valuable trace materials recoverable through emerging extraction processes. The paradigm shift from wastewater disposal to resource recovery is the central intellectual and practical challenge of contemporary water engineering.

This article reviews the full spectrum of wastewater treatment and reuse technologies, from the fundamental unit processes of conventional treatment through to the advanced technologies required for the highest quality reuse applications, and from the established practice of agricultural irrigation with treated effluent to the emerging frontier of direct potable reuse. The Indian regulatory and infrastructure context receives particular attention given the scale of India's treatment deficit and the urgency of developing effective, affordable solutions for rapidly urbanizing Indian cities.

2. Wastewater Characteristics and Composition

2.1 Municipal Wastewater

Municipal or domestic wastewater is the spent water from residential, commercial, and institutional premises, comprising toilet and bathroom wastewater (blackwater), kitchen and laundry wastewater (greywater), and infiltration and inflow from defective sewer pipes and stormwater connections. Its composition reflects the activities generating it and is broadly consistent across urban populations, though significant variation exists with income level, dietary habits, industrial connections to the sewer system, and the degree of stormwater intrusion.

Typical municipal wastewater characteristics include: biochemical oxygen demand (BOD5) of 150 to 300 mg/L representing the oxygen demand of biodegradable organic matter; chemical oxygen demand (COD) of 250 to 600 mg/L representing total oxidizable organic content; total suspended solids (TSS) of 150 to 400 mg/L; total nitrogen of 25 to 60 mg/L comprising ammonium, nitrate, and organic nitrogen; total phosphorus of 4 to 15 mg/L; and microbial populations including 10^6 to 10^9 total coliforms per 100 mL, 10^5 to 10^8 fecal coliforms per 100 mL, and variable concentrations of enteric viruses, Giardia cysts, and Cryptosporidium oocysts. Emerging contaminants — pharmaceuticals, personal care products, endocrine-disrupting compounds, and microplastics — are present at microgram to nanogram per liter concentrations and are not removed by conventional treatment processes.

2.2 Industrial Wastewater

Industrial wastewater composition varies enormously by industry sector and production process, ranging from relatively clean cooling water to highly concentrated process streams containing toxic heavy metals, recalcitrant organic compounds, or extreme pH values that require specialized pre-treatment before discharge to municipal sewers or direct treatment and disposal. The principal industrial wastewater-generating sectors in India include textiles (high color, BOD, and total dissolved solids from dyeing and finishing processes), food processing (high BOD and nutrients from organic waste), pharmaceuticals (complex organic compounds and

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active pharmaceutical ingredients), electroplating (heavy metals including chromium, nickel, and cadmium), tanneries (chromium, sulfides, and high organic loads), and sugar mills (very high BOD from molasses and wash water).

India's environmental regulations require industries discharging to municipal sewers to meet General Standards for discharge to inland surface waters under the Environment Protection Act and specific industry-sector standards issued by the Central Pollution Control Board. Enforcement of these standards has historically been inadequate, with industrial effluent contributing disproportionately to the organic and toxic load reaching municipal sewage treatment plants and receiving water bodies. The Common Effluent Treatment Plants (CETPs) established for industrial clusters — particularly small-scale industries in textile, leather, and electroplating clusters — represent a collective treatment approach that makes specialized treatment economically viable for individual small enterprises.

3. Primary Treatment

Primary treatment removes settleable and floatable solids from wastewater through physical separation processes, reducing TSS by 50 to 70 percent and BOD by 25 to 40 percent. It does not remove dissolved pollutants, nutrients, or pathogens. The unit operations of primary treatment are screening, grit removal, and primary sedimentation.

Screening removes coarse solids — rags, plastic bags, sanitary products, and food scraps — using fixed or mechanically cleaned bar screens with clear openings of 6 to 25 mm for coarse screens and 1 to 6 mm for fine screens. Grit removal in grit chambers or vortex separators removes dense inorganic particles — sand, grit, and small gravel — that would otherwise abrade pump impellers, clog pipes, and accumulate in subsequent biological treatment tanks. Primary sedimentation in circular or rectangular tanks with detention times of 1.5 to 2.5 hours removes the settleable fraction of suspended solids as primary sludge, which settles to the tank floor and is withdrawn as a thick slurry for further processing.

Chemically enhanced primary treatment (CEPT) improves primary clarifier performance by adding coagulants — typically ferric chloride, alum, or polyaluminium chloride — to the primary influent, inducing flocculation of fine colloidal particles that would not settle in a conventional primary clarifier. CEPT can achieve TSS removals of 80 to 90 percent and BOD removals of 50 to 70 percent, substantially improving the effluent quality entering secondary treatment or, in developing country contexts where full secondary treatment is not available, providing adequate treatment for discharge to rivers receiving significant dilution. Several Indian cities including Mumbai and Kolkata operate CEPT-enhanced primary treatment plants as the first stage of planned sequential upgrades to full secondary treatment.

4. Secondary Treatment

4.1 Activated Sludge Process

The activated sludge process (ASP) is the most widely used biological secondary treatment technology worldwide, employed in the majority of large municipal sewage treatment plants in India and globally. In the ASP, wastewater is mixed with a culture of aerobic microorganisms — the activated sludge — in an aeration tank, where bacteria oxidize the dissolved and colloidal organic matter to carbon dioxide and water, and incorporate the oxidized matter into new bacterial biomass. The mixed liquor is then separated in a secondary clarifier where the bacterial biomass settles to form return activated sludge (RAS), recycled to the aeration tank to maintain the active microbial population, and waste activated sludge (WAS), withdrawn for sludge

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processing. Well-operated ASP plants achieve BOD removals of 90 to 95 percent, TSS removals of 85 to 95 percent, and fecal coliform reductions of 2 to 3 log units.

The conventional ASP can be modified to achieve biological nutrient removal (BNR) in addition to organic matter removal, addressing the eutrophication potential of nutrient-rich effluents discharged to sensitive receiving waters. Biological nitrogen removal requires alternating aerobic and anoxic zones — the Bardenpho and Ludzack-Ettinger processes — in which nitrifying bacteria first convert ammonium to nitrate in aerobic conditions, followed by denitrifying bacteria that reduce nitrate to nitrogen gas in anoxic conditions. Biological phosphorus removal exploits the enhanced phosphorus uptake capacity of certain bacteria under alternating anaerobic and aerobic conditions. Combined biological nitrogen and phosphorus removal systems can achieve total nitrogen below 10 mg/L and total phosphorus below 1 mg/L in well-operated plants.

4.2 Sequential Batch Reactors

Sequential batch reactors (SBRs) are a fill-and-draw variation of the activated sludge process in which the treatment cycle — filling, reaction, settling, and decanting — occurs sequentially in a single tank rather than continuously in separate tanks. SBRs offer operational flexibility, compact footprint compared to continuous-flow ASP, and inherent suitability for biological nutrient removal through timed alternation of aerobic and anoxic conditions within the reaction phase. They are particularly appropriate for small to medium treatment plants (up to approximately 50 MLD) and for locations with variable flow patterns where the flexible batch operation can accommodate flow variability more readily than continuous-flow processes.

India's Ministry of Housing and Urban Affairs has identified SBR technology as preferred for new sewage treatment plants under the Sewerage and Septage Management sub-program of AMRUT, citing its compact footprint, good nutrient removal performance, and suitability for phased construction. A significant number of new urban STPs in India have been designed and constructed using SBR technology in the past decade, with some of the best-performing plants achieving effluent quality approaching tertiary standards.

4.3 Upflow Anaerobic Sludge Blanket (UASB) Reactors

The upflow anaerobic sludge blanket (UASB) reactor is an anaerobic biological treatment process developed at Wageningen University in the Netherlands in the 1970s and subsequently adopted widely in tropical and subtropical developing countries, including India, Brazil, and Colombia, as a cost-effective alternative to energy-intensive aerobic secondary treatment. In the UASB, wastewater flows upward through a dense blanket of anaerobic granular sludge, which degrades the organic matter through a consortium of hydrolytic, acetogenic, and methanogenic bacteria, converting it to biogas — a mixture of methane and carbon dioxide — without the aeration energy cost of aerobic processes.

UASB reactors achieve BOD removals of 70 to 85 percent at hydraulic retention times of 4 to 8 hours for warm-climate municipal wastewater, at energy costs 3 to 5 times lower than equivalent aerobic processes and generating biogas that can be used for on-site energy generation. However, the UASB effluent does not meet discharge standards in most jurisdictions without post-treatment, typically an aerobic polishing step such as an activated sludge unit, extended aeration, or a constructed wetland. The combination of UASB primary treatment with aerobic polishing is a cost-effective two-stage treatment configuration well-suited to Indian conditions, deployed in multiple Indian cities including Kanpur and Pune.

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5. Tertiary and Advanced Treatment

5.1 Filtration and Disinfection

Tertiary treatment polishes secondary effluent to remove residual suspended solids, turbidity, nutrients, and pathogens to levels appropriate for discharge to sensitive receiving waters or for reuse applications. Tertiary filtration using rapid sand filters, dual-media filters, or continuous backwash upflow filters reduces TSS to below 5 mg/L and turbidity to below 2 NTU, essential prerequisites for effective downstream disinfection and membrane processes. Coagulation and flocculation upstream of tertiary filters further improve particle removal and can reduce phosphorus to below 0.5 mg/L when combined with chemical precipitation.

Disinfection eliminates or inactivates pathogenic microorganisms in the treated effluent. Chlorination — the addition of chlorine gas or sodium hypochlorite — has been the dominant disinfection technology for over a century, providing effective bacterial inactivation at low cost. However, chlorine reacts with organic matter in the effluent to form disinfection by-products (DBPs) including trihalomethanes and haloacetic acids that are carcinogenic at elevated concentrations, limiting effluent chlorine doses and motivating the adoption of alternative disinfection methods. Ultraviolet (UV) disinfection, which inactivates pathogens through direct DNA damage without chemical addition or DBP formation, has become the preferred disinfection technology for effluents destined for reuse, with reliable 4-log pathogen inactivation achievable at UV doses of 40 to 100 mJ/cm2.

5.2 Membrane Bioreactors (MBR)

The membrane bioreactor (MBR) integrates biological treatment with membrane filtration — typically hollow-fiber or flat-sheet ultrafiltration membranes with pore sizes of 0.01 to 0.4 micrometers — in a single process stage, replacing the conventional secondary clarifier with direct membrane separation of treated effluent from the biological mixed liquor. The membrane provides an absolute barrier to bacteria, protozoa, and suspended solids, producing a consistently high-quality effluent with turbidity below 0.2 NTU, TSS below 1 mg/L, and fecal coliform counts below 10 CFU/100 mL regardless of feed quality or flow variability — performance that is simply not achievable in conventional secondary clarification.

MBR technology has advanced dramatically since its commercial introduction in the early 1990s, with membrane costs declining by over 90 percent, energy consumption falling from over 3 kWh/m3 to below 0.5 kWh/m3 in the most efficient modern systems, and the technology scaling from small package plants to large municipal installations processing over 100,000 m3/day. The superior and consistent effluent quality of MBR makes it the treatment of choice as a pre-treatment step for reverse osmosis in water reuse schemes, and its compact footprint is particularly advantageous in land-constrained urban locations. MBR plants are operating in Hyderabad, Chennai, and multiple other Indian cities for industrial wastewater treatment and some municipal applications.

5.3 Reverse Osmosis (RO)

Reverse osmosis is a pressure-driven membrane separation process that removes dissolved salts, organic compounds, and virtually all microbial contaminants from water by forcing it through semi-permeable membranes with pore sizes in the range of 0.0001 micrometers — small enough to exclude hydrated salt ions. In wastewater reuse applications, RO follows tertiary treatment or MBR to remove residual dissolved organic carbon, nutrients, pharmaceuticals, and trace contaminants to concentrations below detection limits, producing a high-purity product water suitable for the most demanding applications including indirect and

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direct potable reuse, semiconductor manufacturing process water, and boiler feed water.

RO operates at applied pressures of 8 to 25 bar for brackish water and secondary wastewater treatment, with water recoveries of 75 to 85 percent in well-designed systems — meaning that 15 to 25 percent of the feed becomes a concentrated brine reject stream requiring disposal. The energy consumption of RO treatment is 0.3 to 1.0 kWh/m3 for modern energy recovery systems, substantially higher than biological treatment but acceptable in the context of producing high-quality reclaimed water that substitutes for expensive freshwater. Membrane fouling — the deposition of organic matter, biological growth, and scaling compounds on membrane surfaces — is the primary operational challenge of RO in wastewater reuse, requiring careful pre-treatment, chemical cleaning protocols, and membrane replacement programs.

5.4 Advanced Oxidation Processes (AOPs)

Advanced oxidation processes generate highly reactive hydroxyl radicals (OH•) — the most powerful oxidant accessible in water treatment — through the combination of ozone, hydrogen peroxide, and ultraviolet light in various configurations. Hydroxyl radicals react rapidly and non-selectively with virtually all organic compounds, oxidizing them to carbon dioxide and water or transforming them to less harmful intermediate products. AOPs are particularly important for the destruction of trace organic contaminants — pharmaceuticals, endocrine disruptors, pesticides, industrial solvents — that are recalcitrant to biological treatment and are not removed by RO.

The principal AOP configurations used in wastewater treatment and reuse include ozone alone (effective for many pharmaceuticals and for color removal), UV/H2O2 (effective for chloramines, nitrosamines, and many pharmaceuticals), and ozone/H2O2 (the most cost-effective configuration for a broad spectrum of trace organic contaminants). The multiple-barrier treatment train employed in Singapore's NEWater scheme — MBR or conventional secondary treatment followed by UF, RO, and UV/AOP — achieves removal of all target trace organic contaminants to below detection limits and provides the safety assurance required for indirect potable reuse through reservoir blending.

5.5 Constructed Wetlands

Constructed wetlands are engineered systems that use the physical, chemical, and biological processes of natural wetland ecosystems — plant uptake, microbial degradation, sedimentation, filtration, and adsorption — to treat wastewater in a low-energy, low-cost configuration appropriate for small communities, rural areas, and developing country contexts where energy and operational skill availability are limited. The two principal configurations are surface flow wetlands, in which wastewater flows above a gravel or soil substrate planted with emergent macrophytes such as Phragmites australis (common reed) or Typha (bulrush), and subsurface flow wetlands, in which water flows horizontally or vertically through a planted gravel medium without exposure at the surface, reducing odor and mosquito breeding risk.

Well-designed subsurface flow constructed wetlands treating secondary effluent can achieve BOD below 20 mg/L, TSS below 20 mg/L, and fecal coliform reductions of 2 to 3 log units at hydraulic loading rates of 20 to 80 mm/day, making them suitable for effluent polishing to meet discharge standards for non-sensitive receiving waters or for unrestricted agricultural irrigation following additional disinfection. Their very low energy requirements (gravity flow, no electrical infrastructure needed), low operational complexity, and dual function as wildlife habitat and landscape amenity make them particularly attractive for Indian small towns

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and rural areas with limited institutional and financial capacity for mechanical treatment systems.

6. Comparative Treatment Performance

Table 1 presents a comparative summary of the key treatment technologies reviewed above, evaluating their performance across principal water quality parameters and indicating their suitability as standalone or combined treatment stages:

Treatment Process	BOD Removal (%)	TSS Removal (%)	Pathogen Log Reduction	Nutrients Removed	Energy Use (kWh/m3)
Primary (sedimentation)	25-40%	50-70%	< 1 log	None	0.05-0.10
CEPT	50-70%	80-90%	< 1 log	P (partial)	0.10-0.20
Activated sludge (ASP)	90-95%	85-95%	2-3 log	With BNR mod.	0.30-0.60
UASB reactor	70-85%	60-75%	1-2 log	None	0.05-0.10 (net)
SBR	90-96%	85-95%	2-3 log	N and P possible	0.25-0.50
MBR	95-99%	>99%	4-5 log	With BNR mod.	0.40-0.80
Tertiary sand filter	Polishing	TSS < 5 mg/L	0.5-1 log	None	0.05-0.10
Reverse osmosis	>99%	>99%	6+ log	N and P removed	0.30-1.00
UV disinfection	None	None	3-6 log	None	0.02-0.10
Constructed wetland	75-95%	70-90%	2-3 log	N and P (partial)	0.01-0.05

Table 1: Comparative treatment performance of principal wastewater treatment technologies

7. Wastewater Reuse Categories and Quality Requirements

7.1 Agricultural Irrigation

Agricultural irrigation is the largest category of water use globally — accounting for approximately 70 percent of freshwater withdrawals — and offers the greatest volume potential for wastewater reuse. The WHO 2006 Guidelines for the Safe Use of Wastewater, Excreta and Greywater in Agriculture define health-based targets for wastewater reuse in unrestricted irrigation (where crops are eaten raw) and restricted irrigation (food crops not eaten raw, fodder, fiber), with the most restrictive target of less than 10^-6 disability-adjusted life years (DALYs) per person per year achievable through combinations of wastewater treatment and agronomic practices.

Unrestricted irrigation of vegetables and fruits consumed raw requires pathogen removal to below 1 helminth egg per liter and E. coli below 10^3 CFU/100 mL, achievable through a treatment train of secondary treatment followed by tertiary filtration and disinfection. Restricted irrigation of cereal crops, industrial crops, and pasture can be practiced with lower treatment levels when appropriate agronomic controls — cessation of irrigation before harvest, drip irrigation that avoids product contact with effluent — are applied. Nutrient-rich

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treated wastewater provides significant agronomic value as a fertilizer, with typical secondary effluent containing nitrogen (25 to 40 mg/L) and phosphorus (5 to 10 mg/L) concentrations equivalent to substantial quantities of commercial fertilizer.

7.2 Industrial Process Water Reuse

Industrial process water represents the second-largest water use sector and offers significant reuse potential because many industrial applications — cooling tower make-up water, boiler feed water, process rinsing, and dust suppression — do not require potable-quality water. Cooling water, which accounts for the majority of industrial water use in power generation and manufacturing, requires control of Legionella, biofouling, scale deposition, and corrosion but does not require removal of dissolved organics or nutrients to the levels demanded by potable standards. Secondary or tertiary treated municipal effluent meets cooling water quality requirements with appropriate water treatment chemical programs.

Boiler feed water and high-purity process water in semiconductor, pharmaceutical, and food manufacturing require much higher quality — typically with total dissolved solids below 1 mg/L and total organic carbon below 50 micrograms per liter — achievable only through RO followed by deionization. The premium commanded by water of this quality, combined with the growing scarcity and cost of freshwater in industrial locations, provides the economic justification for sophisticated treatment systems that recover and recycle wastewater within industrial facilities or use highly treated municipal effluent as a cost-effective substitute for freshwater abstraction.

7.3 Groundwater Recharge

Indirect potable reuse through managed aquifer recharge (MAR) — the intentional injection or infiltration of treated wastewater into groundwater aquifers from which water is subsequently abstracted, treated further, and supplied as drinking water — provides an additional purification barrier through soil passage and aquifer residence time that substantially reduces the concentrations of residual trace organic contaminants and pathogens present even in highly treated reclaimed water. Soil aquifer treatment (SAT) through infiltration basins can achieve further reductions in BOD, turbidity, and pharmaceutical compounds as water percolates through the vadose zone, while underground residence time of months to years provides a temporal and spatial buffer between recharge and abstraction.

MAR through infiltration basins and injection wells is practiced at significant scale in California, Israel, Australia, and increasingly in India, where the Central Ground Water Board has identified over 1,000 sites suitable for managed aquifer recharge and is promoting artificial recharge schemes as a component of India's National Water Policy. The Shafdan reclamation plant in Israel, operational since 1977, recharges approximately 130 million cubic meters per year of tertiary-treated municipal effluent into the Coastal Aquifer of Israel, from which it is subsequently abstracted, subjected to additional treatment, and used for unrestricted agricultural irrigation — a well-documented example of managed indirect reuse that has operated safely for over four decades.

7.4 Direct and Indirect Potable Reuse

Potable reuse — the treatment of wastewater to drinking water standards for direct or indirect human consumption — represents the most demanding and contentious application of wastewater reuse technology, yet it is increasingly necessary in water-scarce regions where conventional freshwater resources are exhausted

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or inadequate to meet growing demand. Indirect potable reuse (IPR) involves an environmental buffer — a reservoir, lake, or aquifer — between the reclaimed water discharge and the potable supply intake, providing both additional treatment and a degree of psychological distance from the perception of recycled water.

Direct potable reuse (DPR) involves the treatment of reclaimed water to drinking water standards and its introduction directly into the potable water distribution system without an environmental buffer. Windhoek, Namibia has operated the world's longest-running DPR scheme since 1968, treating municipal effluent through a multi-barrier process and blending the product directly into the city's drinking water system. The scheme has operated without a single documented public health incident attributable to reclaimed water over more than 50 years, providing compelling evidence that engineered systems with multiple treatment barriers and rigorous monitoring can reliably produce water safe for direct human consumption.

Singapore's NEWater program, which produces approximately 40 percent of the city-state's water needs through a treatment train of MBR or conventional secondary treatment, ultrafiltration, reverse osmosis, and UV/advanced oxidation, and introduces the product primarily into reservoirs for blending with raw water (indirect potable reuse), with a small proportion used directly in high-technology manufacturing, demonstrates the application of DPR principles at national scale. NEWater's quality exceeds WHO drinking water guidelines for all tested parameters, and the program is supported by rigorous public communication and ongoing monitoring that has built public confidence in reclaimed water quality.

8. Water Quality Standards for Reuse Applications

Table 2 presents a comparison of treated wastewater quality requirements for principal reuse categories, based on WHO guidelines, Indian CPCB standards, and US EPA guidelines for water reuse:

Reuse Category	BOD (mg/L)	TSS (mg/L)	E. coli (CFU/100mL)	Turbidity (NTU)	Required Treatment
Restricted irrigation	< 30	< 50	< 10,000	< 10	Secondary + basic disinfection
Unrestricted irrigation	< 10	< 10	< 1,000	< 2	Secondary + tertiary + disinfection
Vegetables (raw eaten)	< 10	< 5	< 200	< 2	Secondary + tertiary + UV
Industrial cooling water	< 30	< 30	< 10,000	< 5	Secondary + chlorination
Industrial process water	< 5	< 2	Not detected	< 0.5	MBR + RO
Groundwater recharge	< 5	< 2	< 10	< 2	Secondary + tertiary + UV
Indirect potable reuse	< 2	< 1	Not detected	< 0.2	MBR + RO + UV/AOP
Direct potable reuse	< 1	< 0.5	Not detected	< 0.1	MBR + RO + UV/AOP + monitoring

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Table 2: Water quality requirements for principal wastewater reuse categories

9. Sludge Management and Resource Recovery

9.1 Sludge Treatment and Disposal

Wastewater treatment generates substantial volumes of sludge — the concentrated solids removed from wastewater through primary sedimentation and biological secondary treatment. The management of this sludge is a major operational and environmental challenge, representing 40 to 60 percent of total plant operating costs in many sewage treatment plants. Raw sludge contains pathogens, heavy metals (in plants receiving significant industrial influent), organic micropollutants, and objectionable odors, requiring treatment before any beneficial use or safe disposal.

Anaerobic digestion of sludge in heated enclosed digester tanks at mesophilic temperatures (35 to 37 degrees Celsius) or thermophilic temperatures (55 to 60 degrees Celsius) reduces sludge volatile solids by 40 to 60 percent, virtually eliminates pathogens, and generates biogas (60 to 70 percent methane) that provides useful energy. A well-designed large-scale STP can achieve energy self-sufficiency or even net energy export through the combination of anaerobic sludge digestion, biogas collection, and combined heat and power generation — a critically important consideration given the high energy costs of conventional aerobic treatment. Several large Indian STPs, including installations in Delhi and Hyderabad, have anaerobic digesters but underperform on biogas capture and utilization due to operational and maintenance deficiencies.

9.2 Nutrient Recovery

Wastewater and its associated sludge contain significant concentrations of nitrogen and phosphorus — nutrients essential for food production that are increasingly scarce and costly in their conventional forms. Global phosphorus reserves, primarily mined as rock phosphate, are concentrated in a small number of countries and may be exhausted within one to several centuries at current extraction rates. Recovering phosphorus from wastewater and returning it to agricultural use represents a critical circular economy opportunity.

Struvite precipitation — the controlled crystallization of magnesium ammonium phosphate from phosphorus-rich sludge digester supernatant — recovers phosphorus as a slow-release fertilizer product with agronomic properties comparable to commercial phosphate fertilizers. Commercial struvite recovery systems are operating at scale at several large STPs in Europe, Japan, and the United States, recovering 80 to 90 percent of the dissolved phosphorus in digester reject streams. Nitrogen recovery through stripping and absorption — removing ammonium from digester reject as ammonia gas by raising pH and temperature, and absorbing it into sulfuric or nitric acid to produce ammonium sulfate or nitrate fertilizer — provides a complementary pathway for nutrient circularity. These technologies are at early stages of adoption in India but represent an important future development direction as resource scarcity and nutrient pollution of water bodies increase policy attention.

10. Regulatory Frameworks

10.1 India

India's wastewater treatment and discharge regulatory framework is established by the Environment Protection Act 1986 and administered by the Central Pollution Control Board and State Pollution Control Boards. General Standards for discharge to inland surface waters specify BOD of 30 mg/L, TSS of 100 mg/L, pH of 5.5 to 9, and fecal coliform of 1,000 MPN/100 mL as the minimum required effluent quality, with more

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stringent standards applicable for discharge to coastal waters, land irrigation, and in environmentally sensitive areas. Industry-specific standards — covering over 400 industrial categories — impose additional requirements for sector-specific pollutants including heavy metals, chlorinated solvents, and cyanide.

India currently lacks a comprehensive national policy and regulatory framework specifically addressing wastewater reuse, in contrast to the detailed reuse standards established in the United States, European Union, and Australia. The National Water Policy 2012 encourages recycling and reuse of treated wastewater as a priority water resource, and the Smart Cities Mission and AMRUT have incorporated treated wastewater reuse as an eligible activity, but the absence of national quality standards for specific reuse categories creates regulatory uncertainty that inhibits investment in reuse infrastructure. The Central Ground Water Authority's guidelines for artificial recharge with treated wastewater represent a partial framework for managed aquifer recharge applications, and several states including Maharashtra, Rajasthan, and Tamil Nadu have issued state-level reuse guidelines.

10.2 International Frameworks

The United States EPA's 2012 Guidelines for Water Reuse provide a comprehensive framework covering reclaimed water quality requirements for agricultural, landscape, and environmental reuse, groundwater recharge, industrial reuse, and potable reuse, with specific quality criteria for each application category and recommended treatment processes. Several US states — California, Florida, Arizona, and Texas — have enacted specific water reuse regulations that go beyond the EPA guidelines in addressing potable reuse pathways, reflecting the particularly acute water scarcity conditions in the western United States.

The European Union's Regulation 2020/741 on minimum requirements for water reuse, which entered into force in June 2023, establishes harmonized quality standards for the agricultural irrigation reuse of treated municipal wastewater across all EU member states, addressing the fragmentation of national reuse standards that had impeded cross-border agricultural trade involving reclaimed water. The WHO 2006 Guidelines for the Safe Use of Wastewater, Excreta and Greywater remain the primary international reference framework for developing country contexts, adopting a risk-based approach that emphasizes health-based targets and recognizes that multiple barriers — treatment, agricultural management, and personal hygiene — collectively determine health outcomes rather than treatment alone.

11. Emerging Contaminants and Future Challenges

11.1 Pharmaceuticals and Microplastics

The presence of trace organic contaminants in wastewater and treated effluents — pharmaceuticals and their metabolites, personal care products, endocrine-disrupting compounds, pesticides, and industrial chemicals — at concentrations ranging from nanograms to micrograms per liter represents an emerging challenge that conventional treatment processes are not designed to address. Antibiotics discharged in wastewater contribute to the selection and proliferation of antibiotic-resistant bacteria and antibiotic resistance genes in aquatic environments, with potential public health implications that are only beginning to be understood. Hormones and endocrine-disrupting compounds including synthetic estrogens, bisphenol A, and phthalates are detected at concentrations sufficient to cause reproductive and developmental effects in aquatic organisms in many receiving waters.

Microplastics — fragments below 5 mm derived from degradation of larger plastic items and from synthetic textile fibers released during laundering — are ubiquitous in municipal wastewater and are incompletely removed by conventional treatment processes, with secondary effluent typically containing 1 to 20

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microplastic particles per liter. Their persistence in aquatic environments, uptake by aquatic organisms, and potential to transport associated toxic chemicals into food chains are subjects of intensive research. Regulatory attention to microplastics in wastewater is increasing rapidly, with the EU and several national regulators developing monitoring requirements and, in some cases, emission limit values.

11.2 Energy Consumption and Carbon Footprint

Wastewater treatment is an energy-intensive activity — a conventional activated sludge plant treating 100 MLD consumes approximately 30,000 to 50,000 kilowatt-hours per day, equivalent to the electricity demand of 10,000 to 17,000 Indian households. As India scales up its sewage treatment capacity toward the treatment of its full wastewater generation — an increase of over 100 percent from current installed capacity — the associated increase in electricity demand and carbon emissions is a significant concern in the context of India's climate commitments.

Energy-neutral or energy-positive wastewater treatment — in which biogas from anaerobic sludge digestion or direct anaerobic treatment generates sufficient electricity to offset or exceed the plant's own energy demand — is achievable in large plants and is the design target for the most advanced sustainable wastewater treatment facilities. Research directions that will reduce the energy footprint of wastewater treatment include mainstream anaerobic treatment of municipal wastewater at ambient temperatures, microbial fuel cells that directly convert organic matter in wastewater to electricity, and process intensification through advanced aeration control and sidestream nitrogen removal that reduce aeration energy requirements by 20 to 40 percent.

12. Future Directions: The Circular Water Economy

The transformation of wastewater treatment from a disposal-focused to a resource-recovery-focused enterprise — the circular water economy — is the organizing concept for the next generation of wastewater infrastructure. In this framework, the sewage treatment plant is reconceived as a water resource recovery facility (WRRF) that simultaneously recovers clean water for reuse, energy from organic matter, nutrients for agriculture, and potentially other valuable materials from wastewater streams.

Key developments that will drive the transition to the circular water economy include:

- Widespread adoption of anaerobic digestion at Indian STPs for biogas production and energy self-sufficiency, currently practiced in very few Indian plants despite its well-established technical and economic viability
- Development and commercialization of struvite and other nutrient recovery technologies calibrated to Indian sludge characteristics and fertilizer market conditions
- Decentralized wastewater treatment and reuse systems for water-scarce Indian cities and industrial parks, reducing energy and infrastructure costs by treating and reusing water close to the point of generation
- Real-time online monitoring of effluent quality using electrochemical sensors, fluorescence spectroscopy, and DNA-based methods for pathogen detection, enabling dynamic treatment optimization and regulatory compliance verification
- Mainstream application of MBR technology for new Indian municipal STP construction, leveraging falling membrane costs to achieve reuse-quality effluent as the standard treatment output rather than a premium

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- Development of India-specific guidelines and standards for industrial and agricultural wastewater reuse, providing the regulatory certainty needed to attract private investment in reuse infrastructure
- Integration of wastewater heat recovery through heat pumps in cold-climate applications and the exploration of pharmaceutical compound recovery from pharmaceutical manufacturing wastewater through selective adsorption and extraction

13. Conclusion

Wastewater treatment and reuse technologies have advanced to the point where water of any quality — from agricultural irrigation to direct potable supply — can be reliably produced from municipal or industrial wastewater through appropriate combinations of biological, physical, and chemical treatment processes. The multiple-barrier treatment trains demonstrated at Singapore's NEWater program, Windhoek's DPR scheme, and Israel's Shafdan MAR system prove beyond reasonable doubt that engineered water reclamation systems, operated with rigorous monitoring and quality assurance, can consistently produce water meeting or exceeding the most stringent drinking water quality standards.

The challenge for India and for the developing world more broadly is not technical but institutional, financial, and political. The installation and operation of sewage treatment infrastructure at a scale proportionate to the volume of wastewater generated — covering the current 56 percent treatment gap — requires sustained investment, capable institutional management, reliable power supply, and enforceable regulatory frameworks that ensure plants operate as designed rather than as expensive infrastructure liabilities. India's AMRUT program and the National Mission for Clean Ganga represent significant policy commitments to this investment, but the pace of progress has been insufficient to keep pace with urban growth and the increasing pressure on receiving water bodies.

The paradigm shift from wastewater disposal to resource recovery offers a compelling reframing of the investment case for wastewater infrastructure. A sewage treatment plant that generates biogas energy, recovers nutrients for agriculture, and produces high-quality reclaimed water that can be sold to industrial or agricultural users is not merely a public health and environmental infrastructure investment — it is a productive asset generating revenue streams that can partially or fully offset its operational costs. This reframing is essential to making the business case for the scale of investment needed to address India's wastewater treatment deficit, and to building the political will among city governments, state authorities, and private investors to commit to the long-term infrastructure development that water security requires.

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