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Chapter 17

Evaluating sustainability for water and wastewater treatment technologies

Sritama Mukherjee[1]*, Tanmayaa Nayak*[2] *and T. Pradeep*[2*]

[1]Department of Fibre and Polymer Technology, KTH Royal Institute of Technology, Stockholm, Sweden
[2]DST Unit of Nanoscience (DST-UNS) and Thematic Unit of Excellence, Department of Chemistry, Indian Institute of Technology Madras, Chennai, India
**Corresponding author: pradeep@iitm.ac.in*

ABSTRACT

High-performance water and wastewater treatment have become feasible with the development of innovative and advanced technologies that may have the potential to have an impact on health and the environment. At the same time, they can be helpful in protecting the environment and meet specific social needs in a more sustainable way. New purification techniques have the potential to lead to the sustainable development of clean water, understand global environmental challenges and seek ways to improve them. Water treatment processes become more environmentally friendly by reducing energy consumption, removing toxic and essential substances and making products sustainable during the synthesis phase. This chapter discusses water treatment in the context of India, the necessity and methods of assessing sustainability, as well as examples of technological assessments for sustainability.

Keywords: wastewater treatment, sustainability metrics, life-cycle assessment, risk assessment, social impact, green chemistry

17.1 THE WATER AND WASTEWATER TREATMENT SCENARIO IN INDIA

Owing to India's growing population, intensive agriculture, climate change, water pollution, and depleting natural water supplies, water management in India is challenging. Being the world's most populous country, 35% of the Indian population is concentrated in metropolitan regions, while 65% resides in rural areas. According to the 2018 report of NITI (National Institution for Transforming India, Government of India) Aayog, consumption of water could double by 2030, posing serious water scarcity to millions of people and a 6% decline in the country's GDP. Therefore, it is essential to understand and effectively manage our water resources. A sustainable future essentially requires treatment, recycling, and reuse of water. Wastewater treatment becomes crucial because of rapid urbanization and industrialization in the country. This has significant negative impacts on public health and the

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environment. NITI Aayog's report on urban wastewater scenario in India (2022) estimated that for 2020–2021, the wastewater generation in rural areas is predicted to be around 39,604 million litres per day (MLD), whereas it is estimated to be 72,368 MLD in urban areas; out of which 28% of the wastewater is actually treated and the remaining 72% is discharged into aquifers, rivers, and lakes. Inadequate infrastructure, underutilization of treatment capacity, inefficient operation and maintenance and lack of water quality monitoring are some of the primary issues related to the sewage treatment plants.

The Government of India has implemented several policies and programmes to address the issue of water stress in the country. Some of the key policies and programmes include: (1) National River Conservation Plan (NRCP), which aims to improve water quality in the country's rivers by reducing pollution from municipal and industrial sources; (2) Atal Bhujal Yojana, which aims to improve groundwater management by strengthening community-based water management institutions and promoting sustainable groundwater use; (3) National Mission for Clean Ganga (NMCG), which aims to rejuvenate the river Ganga by promoting conservation and management of the river and its tributaries, and (4) National Water Policy, which aims to ensure the conservation and development of water resources through sustainable water management practices. Government and private organizations emphasize on implementing various wastewater treatment methods over the past 10 years. Wetlands, aquifer systems, membrane technology, and biological filters, which are becoming more and more popular alternatives to the traditional activated sludge process (Jadeja *et al.*, 2022). Other initiatives include construction of sewage treatment plants, the promotion of better waste management practices, and the protection of water resources.

At many places, domestic or treated wastewater is used as a source of irrigation, which contains various types of nutrients such as phosphorus, nitrogen, potassium, and sulphur improving the soil fertility that can be easily accumulated by the plants. In that process, it is essential to make sure that the resultant output from the treatment systems conforms to environmental standards particularly with regard to the quality of the treated effluents that are discharged into nature. Centralized sewage and wastewater treatment systems are often too expensive and sophisticated to serve only a section of big cities, while the smaller towns and low-income areas get overlooked. Decentralized wastewater treatment system (DEWATS) are simplified systems for community-based sanitation centres having capacity of 1–1000 m^3/day for treating organic wastewater that is both cost effective and efficient for developing nations. It uses aerobic treatment systems and constructed wetlands. Some working examples of DEWATS in India are: 500 KLD capacity soil biotechnology (SBT)-based DEWATS under New Delhi Municipal Corporation; Phytorid-based DWWTs at Bangalore of capacity 250 KLD; 307 KLD DEWATS in Puducherry; 10 KLD system in Gohri, Uttarakhand, a 12 KLD system serving people in Leh, Ladakh, and many more such treatment plants in bigger and smaller cities (Varma *et al.*, 2022).

Apart from wastewater management, India also suffers from groundwater contamination cases, such as higher fluoride and arsenic concentration in groundwater which exceed the permissible limits. The temporal and spatial distribution of these ions depend on the sources (natural and anthropogenic), process and interactions with environment, and the nature of recharge. AMRIT (Arsenic and Metal Removal by Indian Technology) which is instrumental in supplying arsenic-free water for over 1.2 million people every day, has new nanostructured materials with large adsorption capacities for arsenite and arsenate ions in water in field conditions (Mukherjee *et al.*, 2022). Similarly, filters composed of ferrihydrite nanoparticle (FeOOH)-impregnated hybrid polymeric (polyaniline/nanocellulose) composite to remove fluoride from drinking water using nanochemistry have the potential to be scaled up. This technology is able to reduce fluoride levels below the safety standards prescribed for drinking water (Mukherjee *et al.*, 2020).

17.2 TECHNOLOGICAL ADVANCEMENTS IN WATER TREATMENT

In the last decade, the solar-powered treatment of wastewater has gained vital importance in several parts of the world. In many countries, the application of solar energy for sewage water treatment is demonstrated for high efficiency anaerobic digestion of sludge absorption, advanced oxidation processes for decontamination of industrial effluents, solar photo-Fenton with anaerobic activated sludge in sequencing batch reactor for degrading non-biodegradable pollutants, new photo-catalysts, and photo-Fenton and photo reactor configurations. The solar desalination has the dominated contribution of 57% in desalination market world. Various direct solar desalinations are solar still, solar humidification–dehumidification (HDH) and solar chimney and solar-powered membrane desalination (MD). Solar photo-catalysis using semiconductor nanoparticles and metal complexes for destroying water contaminants and disinfection inactivation of waterborne microbial species has been recently developed (Sansaniwal, 2022).

Cellulose nanomaterials have inherent fibrous nature and remarkable mechanical properties. Due to its low cost, biocompatibility and sustainable source, it has huge potential as a component in water filtration membranes, adsorbents, and scaffolds for removal of inorganic and organic pollutants. Various clay (kaolinite, montmorillonite, bentonite, etc.), biopolymers like chitosan, cellulose, alginates; other polymers such as polyvinyl alcohol, polyvinylpyrrolidone, zeolites, and so on have been used to prepare (nano) composites with graphene oxides, CNTs, alumina, iron oxides, and other metal oxides for removal of water contaminants, most commonly heavy metals. Activated carbon derived from wide range of materials has become one of the cheap and versatile porous alternatives for pollutant scavengers. Some common materials that are used to make activated carbon are bituminous coal, bones, pine sawdust, coconut shells, lignite, petroleum-based residues, peanut, sugarcane bagasse, wastewater treatment sludge, and wood (Jaspal & Malviya, 2020).

Biocatalytic membranes combine the enzyme-based chemical reactions and membrane separation into one single unit, by the method of immobilizing enzymes on the membrane surfaces that results in higher selectivity and process efficiency. Its dual function of catalysis and separation has lower energy consumption leading to smaller footprint, and reduced equipment cost. Oxidoreductase enzymes such as peroxidases and laccases are most commonly used for the catalytic degradation of hazardous organic molecules, while hydrolases including a-amylase, trypsin, lipase, and so on are reported for fouling mitigation. These enzymes hydrolyse various organic compounds and bio-foulants, including starch, proteins, amino acids, lipids, and pectins (Barbhuiya *et al.*, 2022).

Electrospinning method has emerged in recent times to produce new generation membranes of nanofibres that have higher porosity than the conventional membranes used for nano or ultrafiltration. They can perform adsorption and filtration depending upon the nanofibre structure and chemical functionality, for example removal of heavy metals using cellulose acetate nanofibre ion-exchange membranes. Cellulose nanomaterial–polymer blends are also popularly electrospun into fibres, where high nanocellulose concentration gives rise to highly viscous polymer blend that results in larger diameter of fibres with narrower pore-size distributions (Carpenter *et al.*, 2015).

Attempts have been made to resolve some of the problems faced by conventional membranes such as polarized concentration, pressure drop, low mass transfer and high fouling tendencies using three-dimensional (3D)-printed membranes. These patterned and customized membranes can be used for desalination or other water/wastewater treatment-related processes. However, cost, time taken, and ease of production of membranes with 3D printing need to be evaluated before scale up (Yusuf *et al.*, 2020).

Forward osmosis technology naturally transports water through a semi-permeable membrane because of osmotic pressure difference between the draw solution (DS) and feed solution (FS) is the driving force. The increased longevity of the used membrane is due to its ability to prevent fouling and the system requires lower pressure as compared to reverse osmosis. Capacitive deionization (CDI) uses functionalized electrodes and an electric field to separate and recover heavy metal ions and salt ions from wastewater. Selectivity and efficiency of the electrodes are enhanced by adding selective ion-exchange resins on the surface of electrodes for the removal of target ions, for example. CDI is also recently being developed to address the organic contaminants (Bolisetty *et al.*, 2019).

Recent developments in bio-mimetic water treatment membrane design include aquaporins that are highly selective water channel proteins integrated into plasma membranes of biological cells. They allow the cell to maintain its volume and internal osmotic pressure in line with the hydrostatic and osmotic pressure differences. Rejection of pollutants occur based on charge and size. The aquaporin channel's distinct architecture is its hourglass structure which features wide entrance vestibules and a narrow hydrophobic centre that allows the passage of water molecules and blocks all other compounds (Werber *et al.*, 2016). Another technology of bioremediation concerns microbial production of enzymes that can cause destruction and effective breakdown of hazardous water pollutants. Genetically engineered microbes have become a point of interest in environmental biotechnology to remediate hazardous chemicals, xenobiotics, and pesticides.

17.3 CONCEPT OF SUSTAINABILITY, NEED AND WAYS OF TECHNOLOGY EVALUATION

Advanced analysis, development of clean technologies, and environmental policies can mitigate the environmental burden directly and indirectly. Water treatment technologies can be an energy-intensive process that is associated with many economic, environmental, and social impacts, hence any technology, in order to be sustainable, must address all three components of the sustainability triple bottom line: environmental, economic, and societal.

To understand the fundamentals of these parameters, we must first consider some key concepts that make a material or process 'green'. The mnemonics PRODUCTIVELY and IMPROVEMENTS, which represent the essence of the 12 principles of green chemistry and green engineering have been reported by Poliakoff and co-workers (Tang *et al.*, 2005, 2008).

PRODUCTIVELY – (a) **P**revent wastes, (b) **R**enewable materials, (c) **O**mit derivatization steps, (d) **D**egradable chemical products inputs, (e) **U**se of safe synthetic methods, (f), **C**atalytic reagents, (g) **T**emperature, pressure ambient, (h) **I**n-process monitoring, (i) **V**ery few auxiliary substances, (j) **E** factor, maximize feed in product, (k) **L**ow toxicity of chemical products, and (l) **Y**es, it is safe.

IMPROVEMENTS – (a) **I**nherently non-hazardous and safe, (b) **M**inimize material diversity, (c) **P**revention instead of treatment, (d) **R**enewable materials and energy, (e) **O**utput-led design, (f) **V**ery simple, (g) **E**fficient use of mass, energy, space, and time, (h) **M**eet the need, (i) **E**asy to separate by design, (j) **N**etworks for exchange local mass and energy, (k) **T**est the life cycle of the design, and (l) **S**ustainability throughout product life cycle.

17.3.1 Sustainability metrics

Sustainability or green metrics is used as the standard of measurement, based on criteria and indicators, to compare or track performance of a given technology, thereby an attempt of quantifying the progress towards the broader goal of environmental sustainability. Some of the common parameters used to determine sustainability metrics of various technologies are summarized in Table 17.1.

17.3.2 Life-Cycle Assessment

Life-cycle assessment (LCA) is a significant methodology that is commonly used to assess the environmental impact of a technology or product from the extraction of raw materials to its end of life (Chee *et al.*, 2022). LCA was first implemented in the wastewater treatment industry in the 1990s (Corominas *et al.*, 2013). LCA is considered as an effective tool for identifying potential life-cycle impacts of nanotechnologies, and its application in this field has expanded during the past 10 years (Klöpffer *et al.*, 2007).

According to the existing International Standards Organization (ISO) 14040 and 14044 standards, an LCA has four major phases such as: (1) goal and scope, (2) life-cycle inventory, (3) life-cycle impact assessment (LCIA), and (4) interpretation. The goal and scope definition of LCA defines the objective of a study and provides a description of the product system in terms of the system boundaries and a functional unit. Since LCA studies for wastewater treatment were first performed, sludge treatment and disposal have been considered in the system boundaries because of their considerable contribution to the total impacts. In case of LCA of waste water treatment process, many factors

Table 17.1 Various metrics and their corresponding expressions used for sustainability assessment.

Metrics	Expressions
Material efficiency	
Environmental factor (E factor)	$\frac{\text{Mass of the total waste}}{\text{Mass of the final product}}$
Atom economy	$\frac{\text{MW(product)}}{\sum \text{MW(reagents)}}$
Carbon efficiency	$\frac{\text{Amount of carbon in product}}{\text{Total carbon present in reactants}} {*}100$
E-factor based on molecular weight	$\frac{\text{MW of waste by-product}}{\text{MW of final product}}$
Effective mass yield	$\frac{\text{Mass of product}}{\text{Mass of hazardous reagent}} {*}100$
Actual atom economy	Reaction yield* AE
Environmental quotient	E factor * Q Q = quotient If a material is considered to be harmless, Q is 1 and EQ = E, while for toxic materials like heavy metal salts, Q can have value in the range of 100–1000, depending on ease of recycling, toxicity, and other factors.
Mass intensity, or process mass intensity	$\frac{\text{Total mass used in a process or process step}}{\text{Mass product}}$
Material recovery parameter	Materials used in the work-up, reaction, and purification are considered by the material recovery parameter (MRP), including catalysts, reaction solvents, washings for extractions, additives, solvents, and drying agents used in purification methods (MRP in the range of 0–1).
Reaction mass efficiency	For a particular reaction $A + B \rightarrow C$, $\frac{\text{Mass(C)}}{\text{Mass(A)} + \text{Mass(B)}}$
Energy efficiency	
Energy intensity	$\frac{\text{Total process energy}}{\text{Mass of the final product}}$
Waste treatment energy	$\frac{\text{Waste treatment requirements}}{\text{Mass of the final product}}$
Solvent recovery energy	$\frac{\text{Solvent recovery requirement}}{\text{Mass of the final product}}$

Source: Adapted from Mukherjee *et al.* (2022).

such as operation of the plant and environmental impact of construction, demolition phases can be included in system boundaries. The second stage, life-cycle inventory analysis, combines inputs and outputs for every process in the life cycle and adds them up for the entire system (Hellweg & Canals, 2014). The inventory phase data are obtained from actual plants, pilot or lab facilities, expert estimation, related literature, and LCA databases. In the third phase, LCIA, potential toxicological impacts on the ecosystem and human health can be derived and identified with the help of life-cycle inventory phase. Finally, the final phase connects the first three to provide a summary and conclusion of all findings. The interpretation should, in accordance with ISO 14040:2006, include the following: (a) identification of significant issues based on the outcomes of the LCI and LCIA phases of an LCA; (b) evaluation of the study considering sensitivity, completeness, and consistency checks; and (c) limitations, recommendations, and conclusions.

17.3.3 Risk Assessment

Risk assessment (RA) stands for the qualitative and quantitative assessment of the risk that a certain pollutant or mixture of contaminants poses to the environment and human health (Boersema & Reijnders, 2009). RA is used as a path to prevent unacceptably adverse effects that technology systems might have on the environment, human health, resources, economy, and the society. To make sure that the preferred alternative or the generated solution complies with current requirements, it is also used proactively in the development of solutions that represent a controllable risk level (Hauschild *et al.*, 2022). When environmental chemists first recognized the widespread presence of persistent chemicals in the environment and wildlife in the 1960s, the concept of environmental RA was developed (van Straalen *et al.*, 2022). RA comprises of four main phases such as: (a) identification of hazard; (b) effect assessment; (c) exposure assessment, and (d) characterization of risk. Hazard identification is the process of identifying the adverse effects of a certain chemical and evaluation of that particular effect. The pathways, emissions, degradation, and rates of movement of a contaminant are all assessed through exposure assessment in order to determine a predicted environmental concentration (PEC). Effect assessment is the estimation of the causality between a substance's dose or level of exposure and the occurrence and severity of an effect. A predicted no effect concentration (PNEC) can be obtained by extrapolating this causality to till date untested species (Guinée *et al.*, 2017). Risk characterization is an estimation of the PEC/PNEC ratio and also quantifying its uncertainties. The REACH program (registration, evaluation, authorization, and restriction of chemicals) rules state that the ratio of PEC/PNEC greater than 1 triggers action and typically forbids approval.

17.3.4 Societal Acceptance

One of the key requirements for promoting a sustainable technology for commercialization is societal acceptability (Kamali *et al.*, 2019a). It is considered as the overall public's opinion about the relevance of the method to daily life (Kamali *et al.*, 2019b). Therefore, in addition to the environmental, economic, and technical performance of a particular technology, social benefits should be taken into consideration to achieve sustainable growth of wastewater treatment industries. The effectiveness of technology can have a favourable impact on how people perceive it, which could lead to an improvement in the economy including possibilities of new job opportunities due to large-scale productions of nanomaterials and their transportation in an industrial effluent treatment plant. Additionally, it is essential to compare the impacts of several types of spent materials being released from the wastewater treatment plant to the environment.

17.3.5 Economical Assessment

This aspect makes sure that an economically feasible system can continue to create goods and services (Assefa & Frostell, 2007). It is based on the three important factors namely: (a) initial investments; (b) operation cost, and (c) maintenance costs. When it comes to determining the feasibility of a certain technology for an industry, as in the case of wastewater treatment plants, initial investments such as civil works, land cost, and equipment are of crucial significance. Specifications of techniques can be useful for the estimation of the initial investment needed. For example, depending on the type of nanomaterials being employed, the reactor size can be designed using the kinetics of the treatment process as an indicator. When treatments based on nanotechnology are to be implemented, various contributions from the production or acquisition of engineered nanomaterials (ENMs), from labour, and from energy (such as the power needed for ENM-based photocatalysis treatments) should all be considered when estimating operating costs. The implementation of ENMs for the industrial wastewater treatment plants has the potential to significantly lower the maintenance cost of plants as compared to membrane system in which biofilms and dissolved organic compounds arises due to biological activities, fouling by inorganic suspended solids are major contributors to maintenance cost.

17.4 SUSTAINABILITY EVALUATION FOR TREATMENT TECHNOLOGIES

Ibrahim *et al.* (2018) designed a methodology to integrate the different framework components of the environmental, technical, economic, and social factors for assessing sustainability of desalination technologies employed in different places. They determined a set of sub-factors related to the technical details of the desalination technology and assigned them under the most relevant aforementioned three parameters. Each sub-factor was evaluated and valuation was done based on calculation, expert opinion, and literature data (for details please refer to the article), which were finally summed up leading to an aggregated score. Realization of the sub-factors was an important step in the whole process. The relevant sets of sub-factors were as follows: for (a) environmental – extraction of seawater (m^3/day), discharged brine impacts (temperature and salinity increase) (°C, ppm), CO_2 emission (kg CO_2-eq/m^3), other environmental impacts (g/m^3), land use (m^2/m^3) product water/day; (b) techno-economic – technology reliability and robustness, quality of water produced (mg TDS/L), scaling and fouling, levelized cost of water production (\$/m^3), the sensitivity of levelized cost of water production (% increase/decrease), the internal rate of return (IRR) %; (c) social – level of aesthetic acceptability, level of noise, provision of employment (number of employees), technology safety, consumption of fossil fuel (kWh/m^3), where the sub-factors are calculated for the product water.

Mukherjee *et al.* (2019, 2020) calculated the sustainability metrics of ferrihydrite incorporated microcellulose (MCCFH) and nanocellulose/PANI nanocomposites (CNPFH) for the removal of arsenic and fluoride from water, respectively. Composites (Na–Zn–Se) for release of essential minerals to purified (often desalinated) water were also considered for similar evaluation by Ravindran *et al.* (Ravindran *et al.*, 2019). Another ternary oxide-based composite CAlFeC developed for defluoridation was also assessed for the same (Egor *et al.*, 2021). All the four materials were assessed by the parameters, including mass intensity, solvent intensity, reaction mass efficiency, energy consumption, E-factor, and CO_2 emission. The nanocomposites were products of water-based green synthesis, hence exhibited excellent numbers with respect to waste generation (E-factor) and energy consumption, while they still require improving their yield, thus the reaction mass efficiency. These studies on sustainability metrics are summarized in Table 17.2.

The careful selection of treatment technology is crucial for effective mitigation of water issues, considering various factors such as location, weather conditions, and types and quantity of influents (Bassi *et al.*, 2022). Eco-based treatment systems were performed by mimicking natural processes,

Table 17.2 Sustainability metrics for various nanomaterials used in applications for clean water.

Nanomaterials	**Sustainability Metrics**					
	Mass Intensity (kg/kg)	**Water Intensity (kg/kg)**	**Reaction Mass Efficiency (%)**	**Energy Intensity (kW h/kg)**	**E factor (kg/kg)**	**CO_2 emission (mg/kg)**
MCCFH	1.9	29.2	52	2.3	0.3	–
CNPFH	1.84	38.8	54	1.8	0.6	–
Na–Zn–Se	1.204	4.7	83	3.2	0.02	40
CAlFeC	5.68	36.67	17.6	2.0	0.12	–

Source: Mukherjee & Pradeep (2023).

such as using the physiological processes of aquatic plants to filter and adsorb wastewater pollutants. Bigger land requirement, rising land prices, and long operation tenures make these systems very expensive. On the contrary, electro-mechanical treatment systems are often compact in size but are energy intensive. Each water/wastewater treatment technology needs to be evaluated for its initial capital and operational costs to understand the actual cost over a system's lifespan, which concerns the economic viability of the investments in such systems, that is further connected with environmental sustainability concerns. The National Green Tribunal's (NGT) Government of India order (dated 30 April 2019) specified stringent effluent discharge standards on pH, BOD, TSS, COD, N/P total, FC for all the existing and upcoming WWT plants in the country. Economic criteria considered for WWT systems assessment should include: investment, energy requirements, net profit value, maintenance and operational costs, land requirements, transportation, sludge disposal and production, resource consumption and recovery, and cost–benefit analysis. Proper implementation of water treatment technologies in communities requires a thorough analysis of opportunities to benefit from the technology by assessing interest in establishing and maintaining such services. Improved relations between governments and the private sector can develop guidelines for the transition from the typical single-use materials of flow economy to a green circular economy, and to address regulatory conflicts.

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