

Review Article

Eco-friendly and Cost-effective Water Treatment and Wastewater Treatment Technologies: A Review

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Abstract

The escalating global water crisis, driven by population growth, industrialization, and climate change, necessitates urgent advancements in sustainable water and wastewater treatment. Conventional treatment paradigms, while effective, often entail significant operational expenses due to high energy demands, intensive chemical consumption, and complex infrastructure requirements, leading to substantial environmental footprints and making them financially prohibitive for many communities, particularly in developing regions. This abstract critically examines the imperative for shifting towards eco-friendly and economically viable treatment technologies that mitigate these challenges. It explores the inherent limitations of traditional methods, which frequently generate considerable sludge volumes requiring further management and contribute to greenhouse gas emissions, thereby underscoring the pressing need for innovative solutions that prioritize both environmental stewardship and financial accessibility in securing global water resources. This paper reviews a range of emerging eco-friendly and cost-effective technologies poised to revolutionize water and wastewater management. We delve into advanced biological processes such as anaerobic membrane bioreactors and integrated fixed-film activated sludge systems, which promise reduced energy consumption and enhanced contaminant removal, alongside nature-based solutions like constructed wetlands and phytoremediation, lauded for their low operational costs and ecological benefits. Furthermore, the abstract considers innovative hybrid systems, resource recovery approaches that transform wastewater into valuable products (e.g., energy, nutrients), and decentralized treatment options designed for adaptability and scalability. These technologies offer compelling advantages, including minimized chemical usage, lower energy footprints, reduced infrastructure costs, and a substantial decrease in sludge generation, making them particularly attractive for achieving sustainable urban and rural water security. The integration of these solutions holds significant potential to enhance resilience against water stress, promote circular economy principles, and ensure equitable access to clean water globally.

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Keywords

Eco-friendly, Cost-effective, Water Treatment, Wastewater Treatment, Sustainable Technologies, Resource Recovery, Nature-based Solutions, Decentralized Systems, Low-energy

1. Introduction

Water is an indispensable resource for life, ecosystems, and socio-economic development. However, the world is grappling with an unprecedented water crisis characterized by increasing scarcity and pervasive pollution [1-4]. Rapid industrialization, agricultural intensification, urbanization, and climate change have severely degraded water quality and strained freshwater resources, leaving billions without access to safely managed drinking water and adequate sanitation [1-6]. The United Nations Sustainable Development Goal (SDG) 6 aims to "ensure availability and sustainable management of water and sanitation for all" by 2030, underscoring the urgency of effective and equitable water resource management [7-12].

Conventional water and wastewater treatment (WWT) technologies, such as activated sludge processes, chemical coagulation, rapid sand filtration, and chlorination, have been instrumental in safeguarding public health and environmental quality over the past century. However, these centralized, energy-intensive, and chemical-dependent systems often present significant challenges. They are typically characterized by high capital expenditure (CAPEX) and operational expenditure (OPEX), substantial energy consumption leading to a high carbon footprint, reliance on chemical reagents, and the generation of large quantities of sludge that require further treatment and disposal [8-12]. These limitations make them economically prohibitive for many developing regions and environmentally questionable in an era demanding ecological sustainability.

The imperative for a paradigm shift towards more sustainable and resilient water management practices has become undeniable. This shift calls for the adoption of eco-friendly and cost-effective WWT technologies that minimize environmental impact, promote resource recovery (water, energy, nutrients), and are economically viable for diverse contexts, from large urban centers to remote rural communities. Eco-friendly technologies are defined by their reduced energy consumption, minimal chemical usage, lower sludge production, smaller carbon footprint, and potential for resource regeneration. Cost-effectiveness, on the other hand, encompasses both low CAPEX and low OPEX, often achieved through simpler designs, reliance on local materials, lower energy demands, and reduced maintenance requirements [11, 12].

This review article aims to provide a comprehensive overview of various eco-friendly and cost-effective water and

wastewater treatment technologies. It critically examines their underlying principles, highlights their advantages in terms of sustainability and economic viability, discusses their inherent limitations, and explores their practical applications. The article is structured to first establish the rationale for sustainable water management, followed by a detailed discussion of specific technologies for potable water treatment and then for wastewater treatment, including emerging and hybrid systems driven by resource recovery. Finally, it outlines the key challenges to widespread adoption and identifies promising future directions for research and implementation in the pursuit of a global circular water economy.

2. The Imperative for Sustainable Water Management

The traditional "take-make-dispose" linear model of water management is unsustainable in the face of growing water scarcity and pollution [9-13]. A transition towards a more circular and sustainable approach is crucial, driven by several interconnected imperatives:

2.1. Environmental Impact of Conventional Treatment

Conventional WWT plants are significant consumers of energy, primarily for pumping, aeration, and mixing. This energy demand contributes substantially to greenhouse gas (GHG) emissions, exacerbating climate change [16]. Moreover, the extensive use of chemicals (coagulants, flocculants, and disinfectants) can lead to the formation of disinfection by-products (DBPs) and residual chemical pollution in effluent streams [17]. The generation of sludge, a byproduct of biological and physico-chemical processes, also poses an environmental challenge, requiring costly and energy-intensive treatment, dewatering, and disposal, often in landfills, which can release methane and leach contaminants [6].

2.2. Economic Burden and Accessibility

The high CAPEX and OPEX associated with conventional WWT infrastructure are major barriers to their implementation, particularly in developing countries and rural areas where financial resources are limited [1, 12, 14]. This economic hurdle of-

ten translates into a lack of access to safe drinking water and sanitation services for vulnerable populations, perpetuating health disparities and hindering socio-economic development. Eco-friendly and cost-effective technologies are essential for achieving equitable access to water security globally.

2.3. Resource Recovery and Circular Economy

A key shift in sustainable water management is viewing wastewater not merely as a waste stream but as valuable resource containing water, energy, and nutrients [1]. Conventional systems often neglect these potential resources. Eco-friendly approaches actively seek to recover and reuse these valuable components, contributing to a circular economy model. This involves treating wastewater to a quality suitable for various non-potable uses (e.g., irrigation, industrial processes), harnessing biogas from anaerobic digestion for energy, and reclaiming nutrients like nitrogen and phosphorus for agricultural fertilizers [1, 2, 9]. This not only reduces the environmental footprint but also creates economic value, enhancing the overall sustainability of WWT.

2.4. Resilience and Decentralization

Centralized WWT systems are vulnerable to single points of failure, natural disasters, and security threats. Decentralized, modular, and nature-based solutions offer enhanced resilience, allowing for localized treatment and reuse, reducing reliance on long-distance infrastructure, and providing flexibility in response to changing conditions [13]. This approach also empowers local communities in managing their water resources.

The confluence of these factors underscores the critical need for innovative, sustainable, and economically viable water and wastewater treatment technologies that align with the principles of ecological sustainability, resource efficiency, and social equity.

3. Eco-friendly and Cost-effective Water Treatment Technologies (Potable Water)

Access to safe drinking water is a fundamental human right. While advanced treatment processes ensure high water quality, simpler, low-cost, and environmentally benign technologies are crucial for widespread application, especially in resource-limited settings and for small communities [14].

3.1. Natural and Low-energy Filtration Systems

3.1.1. Slow Sand Filters (SSF)

Slow sand filters are among the oldest and most reliable water treatment technologies, known for their simplicity, robustness, and effectiveness [15]. They consist of a careful-

ly graded sand bed, typically 0.6 to 1.2 meters deep, supported by a gravel layer and underdrains. Raw water is allowed to percolate slowly through the sand bed (0.1 to 0.4m/h). The primary treatment mechanism in SSFs is biological, occurring within a gelatinous layer, called the "schmutzdecke" or biological film, which forms on the surface of the sand bed. This biofilm, composed of bacteria, fungi, protozoa, and algae, effectively removes pathogens, suspended solids, and some dissolved organic compounds through a combination of physical straining, adsorption, and biological degradation [16].

SSFs are highly effective in removing turbidity (up to 99%), bacteria (up to 99.99%), protozoa (e.g., *Cryptosporidium*, *Giardia*), and even some viruses. They require no chemicals, consume very little energy (gravity-driven), produce minimal sludge, and have low operational costs. They are robust against fluctuations in raw water quality and require minimal skilled labor for operation [17].

They require significant land area, are sensitive to high turbidity (requiring pre-treatment), and have a slow filtration rate, making them unsuitable for very large capacities without extensive land. They are also less effective at removing dissolved organic chemicals or color [15].

3.1.2. Bio-sand Filters (BSF)

A scaled-down version of SSFs, biosand filters are point-of-use (POU) or household-scale devices designed for intermittent operation. They typically consist of a concrete or plastic container filled with layers of sand and gravel, similar to an SSF. Water is poured into the top, forms a "schmutzdecke" layer, and filters through the sand [18].

BSFs are highly effective in removing turbidity, pathogens (bacteria, viruses, protozoa), and some iron and manganese. They are extremely low-cost to build and operate, require no electricity or chemicals, and can be constructed using local materials. They provide convenient access to safe water at the household level, empowering communities [18].

The filtration rate is low (typically 15-20 liters per hour), making them suitable only for household use. They require periodic maintenance (cleaning the top sand layer) and user education for proper operation. Their effectiveness against some dissolved contaminants (e.g., pesticides, heavy metals) is limited [19].

3.1.3. Riverbank Filtration (RBF)

RBF is a natural pre-treatment technology where surface water (from a river or lake) is drawn through the bank sediments by pumping from wells located some distance from the water body. As the water infiltrates through the alluvial aquifer, it undergoes physical, chemical, and biological purification [20].

RBF provides significant removal of suspended solids, pathogens, biodegradable organic matter, and some micro-pollutants. It often results in water with stable temperature, reduced disinfections by-product precursors, and a lower

environmental footprint compared to direct surface water abstraction and conventional treatment. It is a cost-effective alternative for pre-treatment [20].

Effectiveness depends on the hydro-geological characteristics of the aquifer and the quality of the source water. It may not be sufficient as a sole treatment method for highly contaminated sources and can be limited by aquifer clogging or oxygen depletion, potentially leading to manganese/iron release [21].

3.2. Solar-based Disinfection (SODIS)

Solar water disinfection (SODIS) is a simple, low-cost, and environmentally friendly method for disinfecting drinking water at the household level using only sunlight and clear plastic bottles. Contaminated water is filled into transparent plastic bottles (PET bottles are commonly used) and exposed to direct sunlight for a specified period (typically 6 hours on sunny days, or 2 days on cloudy days) [22]. The combined effect of UV-A radiation (which damages microbial DNA and RNA) and elevated temperature (thermal inactivation) effectively inactivates a wide range of waterborne pathogens, including bacteria, viruses, and protozoa [23].

SODIS requires no energy input, chemicals, or complex infrastructure. It is highly accessible, user-friendly, and relies on readily available materials. It has been proven effective against major waterborne pathogens and is particularly valuable in remote areas or emergency situations [23].

It requires clear plastic bottles, sufficient sunlight, and relatively clear water (turbidity >30 NTU significantly reduces effectiveness). The volume of water treated is limited by the number of bottles, and it does not remove chemical contaminants or improve aesthetic water quality (taste, odor) [22].

3.3. Adsorption Using Low-cost Materials

Adsorption is a physico-chemical process where contaminants adhere to the surface of a solid material. While activated carbon is highly effective, its high cost limits widespread use. Research has focused on utilizing abundant, low-cost, and often waste-derived materials as adsorbents for various water contaminants.

3.3.1. Biochar

Biochar is a carbon-rich porous material produced by the pyrolysis (thermal decomposition in the absence of oxygen) of biomass (agricultural waste, wood residues, animal manure) [24]. Its high surface area, porous structure, and surface functional groups make it an excellent adsorbent for a wide range of pollutants, including heavy metals, organic dyes, pharmaceuticals, pesticides, and some inorganic anions [25].

Biochar production offers a sustainable waste-to-resource approach, diverting biomass from landfills or open burning. It is relatively inexpensive to produce, can be regenerated,

and its application can simultaneously improve soil quality if used as a soil amendment after treatment. It is effective for diverse contaminants [26].

Adsorption efficiency varies significantly based on feedstock, pyrolysis conditions, and target contaminant. Regeneration can be challenging, and some specific contaminants may require modified biochar. Leaching of some components from raw biochar can occur [24].

3.3.2. Agricultural Waste Byproducts

Various agricultural wastes, such as fruit peels (orange, banana, lemon), seed shells (coconut, cashew), rice husks, sawdust, and even industrial byproducts like red mud or fly ash, have been investigated as low-cost adsorbents [27]. These materials often contain natural polymers, cellulose, lignin, and pectin with functional groups capable of binding to pollutants.

They are abundant, renewable, and often available at very low or no cost. Utilizing them for water treatment adds value to waste streams, promoting a circular economy. They can be particularly effective for heavy metals and some organic dyes [28].

Adsorption capacity is generally lower than commercial activated carbon. Their physical stability can be poor, and they may degrade over time. Pre-treatment (e.g., washing, drying, grinding, chemical modification) is often required to enhance their adsorption capabilities, which can add to costs [27].

3.4. Phytoremediation (for Source Water Quality Improvement)

Phytoremediation involves the use of living plants to clean up contaminated soil, water, or air. In the context of water treatment, it primarily applies to improving the quality of source water bodies or pre-treating highly contaminated industrial effluents, rather than direct potable water treatment. Plants can absorb, degrade, or stabilize pollutants through various mechanisms: phytoextraction (uptake and accumulation in plant tissues), phytodegradation (breakdown of contaminants by plant enzymes), rhizofiltration (adsorption and precipitation in the root zone), and phytostabilization (immobilization of contaminants in the soil/sediment) [29].

Phytoremediation is a cost-effective, aesthetically pleasing, and environmentally friendly approach. It uses solar energy, requires minimal maintenance, and can be applied over large areas. It is particularly effective for low concentrations of pollutants and for long-term remediation [29].

It is a slow process, often requiring long retention times. Its effectiveness is limited by the plant species, contaminant type, concentration, and environmental conditions (temperature, pH). Disposal of contaminated plant biomass can be an issue if phytoextraction is used [30]. It is not generally suitable as a standalone method for immediate potable water treatment but as a component of a multi-barrier approach for source water protection.

4. Eco-friendly and Cost-effective Wastewater Treatment Technologies

Wastewater treatment is critical for protecting aquatic ecosystems and public health. Conventional centralized systems are often energy and capital intensive. The following section focuses on technologies that offer sustainable and economically viable alternatives, particularly emphasizing nature-based solutions and resource recovery.

4.1. Nature-based Solutions (NBS) / Ecological Systems

4.1.1. Constructed Wetlands (CWs)

Constructed wetlands are engineered systems that mimic the natural functions of wetlands to treat wastewater. They consist of basins or channels filled with porous media (gravel, sand) and planted with wetland vegetation (e.g., reeds, cattails). Treatment occurs through a combination of physical (filtration, sedimentation), chemical (adsorption, precipitation), and biological processes (microbial degradation, plant uptake) [31]. CWs are broadly categorized into Free Water Surface (FWSF) wetlands, where water flows above the substrate, and Subsurface Flow (SSF) wetlands, where water flows horizontally or vertically through the gravel bed, below the surface [32].

CWs are highly eco-friendly, requiring minimal energy input (gravity-driven), no chemicals, and generating very little sludge. They have low CAPEX and OPEX, provide habitat for biodiversity, enhance landscape aesthetics, and can tolerate flow variations. They are effective in removing BOD/COD, suspended solids, nutrients (nitrogen, phosphorus), and some heavy metals and pathogens [33].

They require significant land area, which can be a constraint in urbanized regions. Performance can vary with temperature (less efficient in cold climates) and requires careful design and maintenance to prevent clogging or short-circuiting. Pathogen removal may not be sufficient for direct reuse without further disinfection [31].

4.1.2. Waste Stabilization Ponds (WSPs)

WSPs (also known as lagoons or oxidation ponds) are large, shallow earthen basins designed to treat wastewater through natural processes involving algae, bacteria, and sunlight. They are typically configured in a series of anaerobic, facultative, and aerobic ponds to achieve different treatment stages [34].

Anaerobic Ponds are deep, anoxic ponds where anaerobic bacteria break down organic matter, producing methane and carbon dioxide. High organic load removal can be obtained.

Facultative Ponds are in intermediate depth, with an anaerobic zone at the bottom and an aerobic zone at the surface (supported by algal photosynthesis). These ponds are effective

for BOD removal and some pathogen inactivation.

Maturation/Aerobic Ponds are shallow, highly aerobic ponds where algae produce oxygen, and high levels of pathogen removal occur due to UV radiation and high pH [34].

WSPs are extremely cost-effective with very low CAPEX and OPEX, minimal energy requirements, and no chemical inputs. They are robust, simple to operate, and highly effective for pathogen removal, especially in maturation ponds. They can serve as a buffer for shock loads and are well-suited for warm climates and rural areas with ample land [35].

They require very large land areas, generate odors if overloaded, and are susceptible to algal blooms that can increase effluent suspended solids. Their performance is temperature-dependent, and effluent quality (especially for some parameters) may not meet stringent discharge standards without further polishing [34].

4.1.3. Algal-bacterial Systems / High-rate Algal Ponds (HRAPs)

HRAPs are advanced pond systems designed to maximize algal growth and nutrient removal while also producing biomass for resource recovery. They are typically shallow, intensively mixed (to prevent stratification and promote light penetration), and provide conditions for symbiotic growth of algae and bacteria [36]. Algae utilize carbon dioxide (from bacterial respiration) and nutrients (nitrogen, phosphorus) for photosynthesis, producing oxygen, which is then used by aerobic bacteria to break down organic matter.

HRAPs offer sustainable treatment by combining wastewater purification with valuable biomass production. The produced algal biomass can be harvested for biofuel, animal feed, or bioplastic production, making them resource-positive. They offer high rates of nutrient removal, oxygen generation (reducing aeration costs), and CO₂ sequestration [37].

They require relatively large land areas, especially for scaling up. Algal harvesting can be energy-intensive and costly, posing a major challenge for economic viability. Performance is sensitive to light, temperature, and pH, and cold climates can limit their effectiveness. Controlling undesirable algal species can also be an issue.

4.2. Anaerobic Treatment Technologies

Anaerobic treatment processes degrade organic matter in the absence of oxygen, producing biogas (methane and carbon dioxide) as a valuable energy source. They are particularly suitable for high-strength industrial wastewaters but are increasingly applied to domestic sewage, especially in decentralized contexts [38].

4.2.1. Up-flow Anaerobic Sludge Blanket (UASB) Reactors

UASB reactors are compact and highly efficient anaerobic

systems where wastewater flows upwards through a blanket of granular anaerobic sludge [39]. As organic matter is degraded, gas bubbles (biogas) are produced, which help to mix the sludge blanket. The granular nature of the sludge allows for high biomass retention and efficient solid-liquid separation.

UASB reactors have low energy requirements (no aeration), produce significantly less sludge than aerobic systems, and generate biogas, which can be captured and used for energy production (making them energy-positive). They are compact, have low CAPEX and OPEX, and are robust against shock loads if well-designed. They are particularly suitable for warm climates [39].

They require a specific start-up period (granulation of sludge). The effluent typically contains dissolved methane, residual organic matter, and pathogens, requiring post-treatment (e.g., aeration, filtration, or constructed wetlands) for discharge or reuse. They are less effective at low temperatures or for low-strength domestic wastewater without modification [40].

4.2.2. Anaerobic Baffled Reactors (ABR)

ABRs consist of a series of compartments separated by baffles, forcing wastewater to flow in an up-and-down pattern through the sludge bed in each compartment [41]. This design improves solids retention time (SRT) independent of hydraulic retention time (HRT), promoting efficient sludge contact and degradation.

ABRs are robust, simple to construct and operate, and less prone to washout than single-stage UASBs. They are effective for treating a variety of wastewaters, including domestic sewage, and produce biogas. They have low energy demands and minimal sludge production [41].

Similar to UASBs, effluent requires post-treatment for higher quality. They can be susceptible to short-circuiting if not properly designed, potentially reducing efficiency. Start-up can be slow, and temperature sensitivity remains a factor [42].

4.2.3. Septic Systems (Enhanced/Decentralized)

Traditional septic systems involve a septic tank for primary treatment (solids settling and anaerobic digestion) followed by a soil absorption field (drain field) for secondary treatment and infiltration. Modern enhanced or decentralized systems often incorporate additional steps like aerobic treatment units (ATUs), constructed wetlands, or sand filters before discharge or reuse [43].

Septic systems are highly cost-effective and suitable for rural and peri-urban areas where centralized sewerage is not feasible. They are decentralized, reducing the need for extensive pipe networks and large treatment plants. Enhanced systems can achieve good effluent quality for localized reuse [43].

Rely on suitable soil conditions for the drain field. If improperly designed or maintained, they can lead to groundwa-

ter contamination (nutrients, pathogens). Sludge pump-out is required periodically. Not suitable for high-density urban areas without significant modifications [44].

4.3. Bio-filters and Aerobic Granular Sludge (AGS)

4.3.1. Bio-filters (Submerged Aerated Filters - SAF)

Bio-filters leverage naturally occurring microorganisms attached to a media (e.g., plastic media, sand, gravel) to treat wastewater. In submerged aerated filters, wastewater flows through a media bed, and air is supplied to maintain aerobic conditions. The biofilm on the media removes organic matter and can facilitate nitrification [45].

Biofilters are compact, robust, and offer good performance stability. They have a smaller footprint than activated sludge systems, are less prone to sludge bulking, and can handle variable loads. They generally require less energy for aeration than conventional activated sludge, especially for lower organic loads [45].

Media clogging can be an issue, requiring backwashing or cleaning. Higher concentrations of suspended solids can reduce efficiency. Sloughing of biofilm can contribute to effluent suspended solids. Energy consumption for aeration, though lower, is still present [46].

4.3.2. Aerobic Granular Sludge (AGS)

AGS technology utilizes microbial biomass that self-aggregates into dense, compact granules, typically in sequencing batch reactors (SBRs). These granules have distinct aerobic and anoxic/anaerobic zones, allowing for simultaneous removal of organic matter, nitrogen, and phosphorus within a single reactor [47].

AGS systems offer remarkable advantages, including a small footprint (due to high biomass concentration and excellent settling properties), significantly lower energy consumption (no need for separate anoxic/anaerobic tanks and reduced aeration volume), and greatly reduced sludge production compared to conventional activated sludge [47]. Excellent effluent quality can be achieved with this compact setup.

Start-up involves a granulation period which can be slow. The system requires careful control and optimization of operating conditions (e.g., feast-famine cycles, shear force) to maintain granule stability. Sensitivity to toxic compounds can be higher [48].

4.4. Resource Recovery Focused Technologies

Moving beyond mere pollutant removal, a new generation of WWT technologies focuses on transforming wastewater into a resource, aligning with circular economy principles [11].

4.4.1. Nutrient Recovery (Phosphorus, Nitrogen)

Phosphorus is a finite resource essential for agriculture,

and its excessive discharge contributes to eutrophication. Nitrogen is also a critical nutrient.

Struvite precipitation is a widely using method in the recovering phosphorus (and ammonia) in the form of struvite (magnesium ammonium phosphate, $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$) from wastewater or sludge digester supernatant is a promising method [49]. Struvite is a valuable slow-release fertilizer.

Algal cultivation is also known as a recovery method for nutrients. As discussed for HRAPs, algae efficiently assimilate nitrogen and phosphorus from wastewater, and the harvested biomass can be used as bio-fuel feedstock or bio-fertilizer [36].

Ion exchange and membrane technologies obtained a significant role in water and wastewater treatments. While sometimes energy-intensive, specialized membranes and ion exchange resins can selectively recover nutrients from concentrated waste streams [50].

4.4.2. Energy Recovery (Biogas from Anaerobic Digestion)

Anaerobic digestion, inherent in UASB and ABR systems, is a cornerstone of energy recovery. Organic matter in wastewater and sludge is converted into biogas (50-75% methane), which can be directly used for heating, electricity generation on-site (co-generation), or upgraded to bio-methane for vehicle fuel or injection into natural gas grids [9]. This offsets significant operational costs and reduces reliance on fossil fuels.

4.4.3. Water Reuse

Treating wastewater to a quality suitable for various non-potable uses (e.g., irrigation, industrial cooling, toilet flushing, and aquifer recharge) significantly reduces demand on fresh water sources. While advanced membrane processes (e.g., reverse osmosis, nano-filtration) are highly effective for producing high-quality reclaimed water, they are energy-intensive [51]. Eco-friendly approaches combine these with more sustainable pre-treatment (e.g., constructed wetlands, bio-filtration) or simpler disinfection methods to reduce overall energy and chemical footprints. For instance, tertiary treatment with maturation ponds or constructed wetlands can achieve water quality suitable for agricultural irrigation [34].

4.4.4. Microbial Fuel Cells (MFCs) and Microbial Electrosynthesis (MES)

These are emerging bio-electrochemical systems that hold promise for simultaneous wastewater treatment and energy recovery.

MFCs methods utilize electrochemically active microorganisms to oxidize organic matter in wastewater at an anode, generating electrons that flow through an external circuit to a cathode, thereby producing electricity [52].

MES method reverses the process, using an external pow-

er source to drive microbial reduction reactions, converting CO_2 or other simple molecules into valuable products (e.g., methane, hydrogen, acetate) while treating wastewater [53].

Both MFCs and MES offer the potential for very low-energy or even energy-positive wastewater treatment, minimal sludge production, and direct conversion of chemical energy in wastewater into electrical energy or valuable commodities.

Currently, power output from MFCs is low, and the technology is generally at the laboratory or pilot scale. The higher CAPEX, electrode fouling and scaling up create some significant challenges on widespread commercialization of these methods [52]. Similarly, MES systems require further optimization for efficiency and product yield.

5. Hybrid and Integrated Systems

Hybrid and integrated systems, which combine two or more different technologies in series or parallel, often offer synergistic benefits, optimizing performance, cost-effectiveness, and sustainability [54]. The goal is to leverage the strengths of each component while mitigating their individual limitations.

5.1. Anaerobic and Aerobic Systems

A common and highly effective hybrid approach involves coupling anaerobic treatment (e.g., UASB, ABR) for high organic load removal and biogas production, followed by aerobic polishing (e.g., constructed wetlands, trickling filters, activated sludge, AGS) for further BOD removal, nitrification, and pathogen inactivation. This maximizes energy recovery while achieving high effluent quality [55]. For example, a UASB-Constructed Wetland system is widely recognized as a sustainable and cost-effective solution for domestic wastewater treatment in developing regions.

5.2. Nature-based Solutions and Decentralized Technologies

Integrating NBS like constructed wetlands or WSPs with decentralized mechanical units (e.g., enhanced septic tanks, small-scale membrane bioreactors in specific zones) can provide robust, resilient, and adaptable solutions for dispersed populations or on-site treatment. This reduces the burden on large centralized infrastructure while still ensuring effective treatment [13].

5.3. Adsorption/Filtration with Biological Systems

Using low-cost adsorbents (e.g., biochar) as a pre-treatment step can effectively remove recalcitrant compounds or heavy metals that are difficult for biological systems to handle, thus protecting the downstream biological process and enhancing overall treatment efficiency. Similarly, post-filtration with

low-cost media can polish effluent from biological systems [26].

5.4. Resource Recovery Integration

Comprehensive integrated systems aim for maximal resource recovery. This could involve anaerobic digestion of sewage sludge and organic fractions of wastewater for biogas, followed by nutrient recovery (struvite precipitation) from the digester effluent, and then a final polishing step (e.g., membrane filtration or constructed wetlands) for water reuse [12].

The development of modular and flexible integrated systems allows for tailored solutions specific to local conditions, wastewater characteristics, required effluent quality, available land, and financial resources. This approach embodies the holistic philosophy of sustainable water management.

6. Challenges and Future Perspectives

While the array of eco-friendly and cost-effective WWT technologies offers promising solutions, their widespread implementation faces several challenges. Addressing these will be crucial for accelerating the global transition towards sustainable water management.

6.1. Challenges

6.1.1. Public Perception and Acceptance

Nature-based solutions like constructed wetlands or WSPs, despite their environmental benefits, can sometimes face public resistance due to perceived aesthetic issues (e.g., mosquito breeding, odors) or lack of understanding regarding their effectiveness [31]. Educating communities and demonstrating successful case studies are vital.

6.1.2. Land Availability

Many eco-friendly technologies, particularly nature-based solutions like CWs and WSPs, require significant land area. This can be a major constraint in densely populated urban areas or regions with high land values [32]. Innovative designs, such as vertical flow wetlands or compact modular units, are being explored to mitigate this.

6.1.3. Performance Variability and Climate Dependency

Biological and nature-based systems are inherently sensitive to environmental conditions (temperature, pH, sunlight). Their performance can fluctuate, especially in extreme climates, requiring robust design and careful operation to ensure consistent effluent quality [34].

6.1.4. Regulatory Frameworks

Existing regulatory frameworks are often prescriptive,

based on conventional centralized technologies. There is a need for more flexible, performance-based regulations that encourage innovation and the adoption of novel, decentralized, and resource-recovering technologies [56].

6.1.5. Scalability and Implementation

While many technologies show promise at lab or pilot scale, scaling them up for real-world applications (especially for municipal or industrial use) can present engineering and operational challenges. Knowledge transfer and capacity building, particularly in developing regions, are essential [10].

6.1.6. Emerging Contaminants (ECs)

Micropollutants like pharmaceuticals, personal care products, and endocrine-disrupting chemicals pose an increasing threat. Many eco-friendly technologies, especially simpler ones, may not be fully effective in removing these ECs, necessitating research into hybrid solutions or advanced, yet sustainable, polishing steps [57].

6.1.7. Operation and Maintenance Expertise

While many eco-friendly systems are designed for simplicity, they still require proper operation and maintenance. Lack of skilled personnel, financial resources for maintenance, and consistent monitoring can lead to system failure, particularly in decentralized settings [58].

6.2. Future Perspectives

6.2.1. Integration with Smart Technologies

The integration of IoT sensors, real-time monitoring, and Artificial Intelligence (AI) can optimize the performance of eco-friendly systems, predict maintenance needs, and enhance energy efficiency, making them more resilient and adaptive [59].

6.2.2. Advanced Materials and Nanotechnology

Development of novel, low-cost, and sustainable adsorbent materials (e.g., modified biochar, graphene-based composites, metal-organic frameworks) with enhanced selectivity and regeneration capabilities for various contaminants, including ECs, is a promising area [60-62].

6.2.3. Next-generation Nature-based Solutions

Developments of further research into optimizing plant selection, media design, and operational strategies for CWs and WSPs to enhance contaminant removal (especially ECs and pathogens) and facilitate resource recovery would be an appropriate solution. Hybrid wetlands and vertical flow systems for urban spaces will gain prominence [32].

6.2.4. Maximizing Resource Recovery

Shifting from "wastewater treatment" to "water resource recovery facilities" is key. Future efforts will focus on maximizing nutrient (nitrogen, phosphorus, potassium), energy (biogas, MFCs), and valuable chemical recovery from diverse wastewater streams, creating new revenue streams and closing resource loops [12].

6.2.5. Decentralized and Modular Systems

The trend towards decentralized, modular, and containerized WWT solutions will continue, enabling flexible deployment in different contexts, from remote communities to specific industrial sites, reducing reliance on expensive centralized infrastructure [13].

6.2.6. Circular Economy Models

Moving towards a holistic circular water economy where water, energy, and nutrients are continuously reused and recycled, minimizing waste and maximizing efficiency. This requires interdisciplinary collaboration between water engineers, urban planners, agriculturalists, and energy sectors [11].

6.2.7. Climate Change Adaptation and Resilience

Designing WWT systems that are resilient to climate change impacts (e.g., droughts, floods, extreme temperatures) and contribute to climate mitigation (e.g., low GHG emissions, carbon sequestration) will be paramount [6].

7. Conclusion

The global water crisis necessitates a departure from conventional, resource-intensive water and wastewater treatment practices towards more eco-friendly and cost-effective solutions. This review has highlighted a diverse array of technologies that align with principles of sustainability, resource efficiency, and economic viability. From time-tested natural filtration systems like slow sand filters and the household-scale bio-sand filters, to the robust and versatile constructed wetlands and waste stabilization ponds, and the energy-positive anaerobic treatment systems, these innovations offer viable pathways to ensure broader access to safe water and sanitation. Furthermore, the increasing focus on resource recovery through technologies like struvite precipitation, algal cultivation, and emerging bio-electrochemical systems underscore a transformative shift towards a circular water economy, where waste is redefined as a valuable resource.

Despite the significant promise, challenges related to public acceptance, land availability, performance variability, and regulatory inertia need to be proactively addressed. Future research and development must focus on enhancing the efficiency, robustness, and scalability of these technologies, integrating them with smart systems, and exploring novel materials for more effective contaminant removal, including

emerging pollutants. By embracing these sustainable WWT technologies and fostering interdisciplinary collaboration, we can move closer to achieving global water security, protecting vital ecosystems, and building a resilient, resource-efficient, and equitable future.

Abbreviations

SDG	Sustainable Development Goal
WWT	Water and Wastewater Treatment
CAPEX	Characterized by High Capital Expenditure
OPEX	Operational Expenditure
GHG	Greenhouse Gas
SSF	Slow Sand Filters
BSF	Bio-sand Filters
POU	Point-of-use
RBF	Riverbank Filtration
SODIS	Solar Water Disinfection
NBS	Nature-based Solutions
CWs	Constructed Wetlands
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
AGS	Aerobic Granular Sludge
HRAPs	High-rate Algal Ponds
WSPs	Waste Stabilization Ponds
UASB	Up-flow Anaerobic Sludge Blanket
ABR	Anaerobic Baffled Reactors
MFCs	Microbial Fuel Cells
SAF	Submerged Aerated Filters
ECs	Emerging Contaminants
MES	Microbial Electrosynthesis

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Conflicts of Interest

The authors declare no conflict of interests.

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