Revolutionizing Wastewater Reuse: A Critical Review of Innovative Treatment Technologies for a Sustainable Energy-Water Nexus

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***Abstract*—The continuing rise in the global population has increased water demand, thereby intensifying pressure on water resources. As demand exceeds conventional sources, wastewater reuse has emerged as a critical solution. The reuse of treated wastewater, both in the domestic and industrial sectors, has significantly enhanced water security, reducing groundwater stress and energy requirements. Hence, due to the rapid advancement in wastewater treatment, a large volume of articles on techniques for increasing wastewater treatment efficiency and reducing energy costs has emerged. This paper explores the innovative treatment technologies and their integration into wastewater reuse systems in line with the energy-water nexus. Key innovative technologies such as forward osmosis, solar-driven desalination, electrochemical systems and nanotechnology methods, which offer improved treatment efficiency, energy savings and resource recovery potential, are highlighted. Moreover, this paper emphasizes the synergy of treatment technologies with renewable energy sources in demonstrating their significant potential in energy-efficient water recovery and reuse, thereby enhancing energy generation (such as biogas) and stabilizing water flux. The novelty of this work is to critically assess the next-generation wastewater treatment technologies that advocate for environmental sustainability and energy efficiency, thus ultimately contributing to a more resilient and integrated energy-water system.**

***Keywords*—energy-water nexus, sustainability, wastewater reuse, wastewater treatment**

I. Introduction

The growing demand for freshwater resources, driven by a continuous rise in population, industrialization, and urbanization, intensifies global water scarcity. For instance, 104 billion tons of water were consumed in the first 10 days of 2024 [1]. Additionally, the impacts of climate change, particularly increasing droughts, are making water resources more unpredictable and worsening water scarcity. The solutions employed by the water utilities to cope with the water shortage are mainly focused on providing an alternative source of water (e.g., reuse, rainwater harvesting) [2].

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Wastewater reuse through the transformation of wastewater into a usable resource is a sustainable way to alleviate water scarcity. Over the years, the perception of wastewater has changed from being something unwanted to a beneficial resource. This shift towards wastewater treatment drives the desire to extract as much water, energy, and valuable materials from wastewater as possible, thereby making more water available for use and reducing pressure on natural water resources [3]. The reuse of treated wastewater has continued to grow rapidly across Europe, the US, China and Australia, with volume increasing between 10 to 41% per year [4]. Additionally, water treatment is closely linked to energy systems, forming the energy–water nexus, which has become a significant challenge in recent years. Meanwhile, the successful realization of wastewater reuse requires innovative treatment technologies that not only guarantee high-quality water but also enhance energy generation.

The contribution of traditional wastewater treatment methods for water reclamation through physical, chemical, and biological processes is limited by high energy use, heavy chemical application, and the loss of potentially recoverable resources, creating significant sustainability challenges [5]. However, recent advances such as forward osmosis, membrane bioreactors, nanotechnology, solar-driven desalination, and electrochemical systems have shown promising potential to transform wastewater reuse. These technologies not only enhance water recovery but also improve energy and resource recovery, along with process sustainability. The incorporation of renewable energy sources, such as solar, wind, and biomass, into treatment plants boosts efficiency and cuts emissions [6]. This critical review aims to explore the latest advancements in wastewater treatment technologies, focusing on their potential to revolutionize wastewater reuse and contribute to a sustainable energy-water nexus. By examining the principles, practical applications, and prospects of these innovative technologies, this review seeks to provide an understanding of how they can address the challenges of traditional wastewater treatment methods and promote a more sustainable and efficient water management system.

II. Overview of Traditional Treatment Technologies

Wastewater treatment technologies have traditionally depended on well-established processes to treat and reclaim water. These conventional wastewater treatment methods are divided into primary, secondary, and tertiary stages. Each stage is vital to the treatment process, ensuring wastewater is properly treated before reclamation. Table 1 highlights the characteristics of the stages in traditional wastewater treatment.

In the primary treatment stage, particulates, suspended solid loads, and organic matter are removed from wastewater using sedimentation and flocculation. Here, the solids are allowed to pass into the sedimentation segment, where most of the solids settle or float to the surface for removal, thereby reducing the organic load and turbidity of the wastewater before further treatment [6]. Coagulation and flocculation, using a large number of chemicals, are employed to increase the settleability of solid particles [7]. The liquid that remains after primary sedimentation usually contains a huge amount of sludge, which requires an additional treatment process [3].

The secondary stage is a biological treatment approach that utilizes microorganisms, either aerobic or anaerobic, to remove dissolved and suspended organic substances, typically measured as the biochemical oxygen demand (BOD) or chemical oxygen demand (COD) [8, 9]. The presence of aerobic bacteria in this process promotes the oxidation in the dissolution of the organic materials[3]. Thereafter, wastewater flows to circular tanks called secondary clarifiers, where activated sludge sinks to the bottom [10]. Up to 90% of the suspended solid materials in the wastewater are removed at this stage [3].

The organic ions suspended solid nutrients, turbidity, nitrogen, phosphorus, heavy metals, and remaining pollutants from secondary treatment are passed to the tertiary stage to be completely removed. It is generally referred to as a polishing step to ensure the treated water can be reused. Tertiary treatment guarantees the water is free from any toxic compounds that could be harmful to human health. It is important to consider factors such as available technology, nutrient management, and by-products generation when selecting the treatment method [11]. Different tertiary treatment technologies are used to tackle complex pollutants, including membrane separation processes (e.g., ultrafiltration, reverse osmosis, among others) and advanced oxidation processes (AOPs) (e.g., photo-Fenton, photocatalysis, hydrogen peroxide/ultraviolet, ozonation, wet air oxidation, and electrochemical oxidation) [12]. The final step of tertiary treatment is disinfection, which involves treating the effluent with chemical disinfectants such as chlorine, chlorine dioxide, ozone, bromine, and UV radiation [13]. Each stage addresses different pollutants and their removal, resulting in progressively cleaner water. Despite the proven effectiveness and reliability of traditional treatment methods, they face significant limitations in addressing modern wastewater challenges for reuse.

A. *Limitations and Energy Demands*

Despite the traditional methods being the foundation of global wastewater infrastructure, they still face several significant limitations that hinder their effectiveness and efficiency. Traditional techniques often struggle to remediate emerging contaminants such as microplastics, pharmaceuticals, perfluorinated compounds and heavy metals [14]. Also, the polarity and high-water solubility of the contaminant make it difficult to remove by the traditional approach [15]. Furthermore, their energy-intensive nature, associated with aeration, pumping, and sludge treatment, may lead to the release of greenhouse gases, which constrain sustainability [16]. Additionally, these treatment systems find it difficult to enable resource recovery, such as water, energy, and minerals, resulting in inefficiencies and waste, thereby missing opportunities for circular economy benefits [17]. These limitations are critical to understand as they drive the need for more advanced and sustainable treatment technologies. The limitations of traditional wastewater treatment methods underscore the necessity for innovative and advanced technologies. These new approaches aim to enhance efficiency, reduce costs, minimize environmental impacts, and paving the way for more sustainable wastewater management solutions.

TABLE 1: COMPARISON OF TRADITIONAL WASTEWATER TREATMENT STAGES

Treatment Stages	Key Removal Mechanisms	Removal Efficiency	Energy Requirements (kWh/m³)	Ref
Primary	gravity separation, sedimentation, flotation, Screening and grit removal	80-90% reduction in TSS 60-70% reduction in BOD	2	[18-20]
Secondary	activated sludge, trickling filters, anaerobic lagoons and Nitrification-denitrification	85 to 92.1% for organic micropollutants	0.30-1.2	[21, 22]
Tertiary	filtration, adsorption, chemical coagulation, oxidation,- Membrane	Up to 99% for micropollutants	6	[20, 23]

filtration, reverse osmosis and ozonation

III. Innovative Treatment Technologies

Innovative treatment technologies for wastewater are crucial for tackling global water scarcity and pollution challenges. To boost treatment efficiency and enhance sustainability, several new processes have been developed to recover resources and energy from wastewater.

A. Forward Osmosis

Forward Osmosis (FO) is an emerging membrane-based separation technology with promising applications in wastewater treatment, reclamation, and the energy-water nexus. This technology is driven by the osmotic pressure differential between the feed solution (FS) and draw solution (DS), allowing water to diffuse from the lower FS to the higher osmotic pressure (DS) without the assistance of external pressure [24], leading to the extraction of high-quality water [25]. The pore size of FO, which is between 0.3 and 0.5nm, makes it a suitable technology for heavy metals and micropollutant removal, and an ideal choice for desalination (owing to its high solute rejection rate) [26]. Compared to other membrane systems, FO has many advantages, including high efficiency, low energy cost (0.02 kWh/m^3) under certain operational conditions, high antifouling performance, negligible pretreatment of feedwater, low pollution tendency, high water recovery and high salt discharge rate [24, 27, 28]. Due to these advantages, research related to FO is gaining considerable attention among researchers to address the problem of water scarcity. For instance, 99% rejection of perfluorooctanoic acid (PFOA) from wastewater was achieved using FO, with the membrane maintaining 90% water recovery and 96.5% flux recovery after simple cleaning [29]. Elsewhere, 99.8% of COD and 99.7% of total phosphorus rejection rates were achieved at a flux of 6 $L/(m^2. h)$ from municipal wastewater using FO [30]. Also, FO achieved 90% removal of melanoidins, 96% antioxidant activity reduction, and 84% COD rejection from sugarcane molasses distillery wastewater rich in phenolic compounds, with water recovery reaching 70% far exceeding the 35–45% typically reported for reverse osmosis[31].

B. Advanced Oxidation Processes (AOPs)

Advanced Oxidation Processes (AOPs) are a highly effective technique that has been widely adopted for degrading emerging pollutants that cannot be eliminated using traditional methods. Among the radicals these processes rely on, hydroxyl free radicals ($OH^{\bullet}$) possess great electrochemical oxidizing power and strong oxidizing potential (E0 = 2.8 V), enabling AOPs to efficiently oxidize and break down almost all organic compounds into H_2O, carbon dioxide (CO_2), and inorganic ions, through dehydrogenation or hydroxylation [32, 33]. Additionally, the hydroxyl radical has a short life in water, making it easier to be eliminated from the treatment system [34]. Among the key advantages of advanced oxidation processes (AOPs) are their ability to operate under extreme conditions, eliminate contaminants rapidly without producing secondary waste, and achieve highly efficient destruction and complete mineralization of target pollutants owing to their exceptionally high oxidation potential [35]. Different AOPs (including ozonation, Fenton and photo-Fenton, electrochemical, photocatalysis, photochemical, sonolysis and hybrid processes) in accordance with the method of radical generation have been investigated for different wastewater treatments. Jennifer, Sonia [36] demonstrated that the advanced oxidation process (UV/H_2O_2) can dramatically enhance surfactant removal from wastewater up to 94.3 ± 4.3% removal within 60 minutes, reducing concentrations below the discharge limit of 0.5 mg L^{-1}. Under an optimized photocatalytic proxone process, ~82% COD, 91% BOD_5, and ~90% total petroleum hydrocarbon removal were achieved from petroleum wastewater [37]. Similarly, using a high-quality $BiOI/NH_2$-MIL125(Ti) catalyst, the optimized photocatalytic ozonation system achieved 96.2 % oxytetracycline (OTC) removal, 77.2% COD reduction, and 64.2 % TOC reduction, following pseudo-first-order kinetics ($R^2 = 0.99$) [38]. Giri and Golder [39] demonstrated the strong impact of advanced oxidation processes (AOPs) for antibiotic removal by comparing a photo-Fenton process (PFP) with UV/TiO_2 photocatalysis for degrading the fluoroquinolone drug ciprofloxacin (CIP). Under optimal conditions, PFP achieved 93.1% CIP removal and 47.3% mineralization, far outperforming UV/TiO_2 (69.7 % and 27.6 %, respectively).

C. Nanomaterial Approaches

The past few years have witnessed significant growth in the use of nanomaterials for wastewater treatment. Nanomaterials are extremely small, measuring a few nanometres to less than 100 nm, making them an effective method to remove the most challenging contaminants [40]. Due to high surface area and reactivity, electrostatic properties, tunable pore volume, enabling rapid, selective adsorption, strong photocatalytic and antimicrobial activity, recyclability, and cost-efficient, eco-friendly, nanomaterials have the potential to eliminate several pollutants from wastewater [41, 42]. The nanomaterials used for various wastewater treatment are classified as nanoparticles (such as ZnO-NPs, Ag-NPs, FeO-NPs), quantum dots (CdSe-QDs, ZnSe-DQs), nanotubes (carbon NTs, Graphite NTs) and nanospheres (FeO nanosphere, carbon nanosphere, TiO_2 nanosphere)[43]. The supermagnetic iron oxide (Fe_3O_4) and gold–iron oxide ($Au@Fe_3O_4$) nanoparticles, synthesized by Matar and Andac [44] showed exceptional photocatalytic performance, removing methylene blue, crystal violet, and malachite green dyes from water with up to 99% efficiency within 30–70 minutes. The multiwalled carbon nanotubes (MWCNTs) generated from poultry litter removed up to 81.8% of Cr(VI) from synthetic tannery wastewater [45]. Nizam, Hanafiah [46] highlights the powerful role of biomass-derived carbon quantum dots (CQDs) in dye removal and degradation in the batch experiment, 77% of Congo red and 75% of methylene blue were removed

D. Integration with Renewable Energy

The advanced technique can be integrated with renewable energy to enhance water recovery, energy generation, and reduce energy consumption, making it a potential game-changer in achieving sustainable wastewater treatment and addressing the energy-water nexus challenges. The coupling of membranes with various renewable energies, such as solar and wind power, has significantly increased the amount of water produced from wastewater. Furthermore, the integration enhances energy efficiency by decreasing thermal energy demand while producing electricity concurrently [47, 48]. As indicated in Table 2, when advanced treatment systems are combined with renewable energy, water can be produced with minimal energy input. Additionally, the integration can generate electricity simultaneously with water production.

TABLE II. INTEGRATION OF ADVANCED TREATMENT TECHNOLOGIES WITH RENEWABLE ENERGY SOURCES

Treatment Technology	Renewable Energy Source	Water Generated (m3/day)	Electricity Produced (kWh)	Energy Reduction (%)	Ref
Ultrafiltration–nanofiltration (UF–NF) + Solar PV	Solar Photovoltaic	1.2	—	40	[49]
Thermo-Osmotic Energy + Desalination	Low-grade heat	3.9×10^4	1.32	0.24	[50]
Reverse osmosis desalination + salt gradient solar pond	Solar energy	2380.8	—	33.6	[51]
Forward osmosis + Biomass	biowaste	103.2 L/m^2	—	45.1	[52]

IV. CHALLENGES AND FUTURE DIRECTIONS

Despite the promising results demonstrated in this study, several aspects warrant further investigation to make these Innovative treatment technologies globally acceptable for water treatment. First, many advanced processes, such as forward osmosis, thermo-osmotic, and nanotechnology systems, remain at pilot-scale due to fouling, scaling, and long-term reliability issues in real-world application conditions. Additionally, the high capital expenditure and operational costs may limit their economic feasibility, with uncertain returns on investment deterring municipal and industrial implementation [53].

Hence, the implementation of Artificial Intelligence and Machine learning for process optimization can revolutionize wastewater treatment efficiency and adaptability [54]. Furthermore, overcoming non-technical barriers may require the development of supportive, technology-neutral policy instruments and robust public-private partnerships to mitigate investment risk. Moreover, enhancing public awareness and acceptance of recycled water through education and addressing psychological barriers is crucial

V. CONCLUSIONS

For sustainable water management, shifting from conventional wastewater treatment to innovative methods is essential. Emerging technologies such as reverse and forward osmosis, advanced oxidation, and nanocatalytic systems offer higher efficiency, energy recovery, and resource recycling potential. Transforming wastewater reuse will not only strengthen the energy–water nexus but also directly support sustainable development goals. The future of sustainable energy and water security depends heavily on our ability to view wastewater as a valuable and resilient resource rather than simply waste.

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