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Review

Enhancing Energy Efficiency and Resource Recovery in Wastewater Treatment Plants

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Abstract: This paper explores the significant role of Wastewater Treatment Plants (WWTPs) in achieving environmental sustainability, with a particular focus on enhancing energy efficiency, resource recovery, and water reuse. WWTPs are crucial for removing pollutants and recovering resources from wastewater, thereby protecting public health and biodiversity. However, they are also associated with high operational costs, substantial carbon footprints, and energy-intensive processes. This article delves into various strategies and technologies to overcome these challenges, aiming to transform WWTPs from energy consumers to energy-efficient resource recovery hubs. Techniques such as anaerobic digestion and the use of advanced oxidation processes and microbial fuel cells are investigated for their potential in energy recovery and efficiency enhancement. Success stories from around the globe are highlighted to demonstrate the feasibility of transitioning to energy-positive WWTP operations. The integration of water reuse systems is also discussed, highlighting recent advancements that enable treated wastewater to be repurposed for agricultural, industrial, and potable uses, thereby promoting sustainability and water conservation. This paper emphasizes the importance of integrating cutting-edge energy management practices to minimize environmental impacts, reduce operational costs, and contribute to a more sustainable water sector.

Keywords: wastewater treatment; anaerobic digestion; biogas production; biomethane; electricity generation

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1. Introduction

Wastewater treatment (WWT) is a significant process that is required to protect the environment, with an emphasis on effective pollutant removal and resource recovery [1]. It has been reported by the World Health Organization (WHO) that 55.5% of global domestic wastewater was safely treated and converted to potable water in 2020 [2]. Primary, secondary, and tertiary treatment systems are available for WWT for the treatment of large-scale water bodies by combining a variety of physical, chemical, and biological techniques. Natural systems are also involved in land-based applications, where these techniques are employed to manage nutrients and eliminate certain toxins [3]. WWT is necessary to reduce the quantity of hazardous substances such as dissolved organic pollutants in fresh/saltwater sources and safeguard the environment. In the case of industrial effluents, limitations such as the presence of toxins like heavy metals, chemicals, and other hazardous substances must be considered. These toxins can impact the efficiency of treatment processes and pose environmental and health risks. Thus, a variety of methods is employed, including air stripping, chemical oxidation, carbon adsorption, ion exchange adsorption, reverse osmosis, and ultrafiltration, to remove dissolved organic pollutants from water [4].

Therefore, WWT plants (WWTPs) are an essential infrastructural component that protects both biodiversity and public health. However, there are certain challenges that are required to be eliminated, especially in the areas of operational cost, carbon footprint, and general sustainability. These challenges make the processes of WWTPs energy-intensive. Hence, it is necessary to thoroughly analyze the complex relationships between energy consumption and energy recovery associated with WWTPs [5]. It is also essential to understand the opportunities and difficulties that are involved in maximizing energy efficiency in the operation of WWTPs.

The main factor influencing the energy intensity of WWTPs is the significant energy consumption that is associated with essential operational activities such as sludge treatment, aeration, and pumping, with aeration accounting for 45 to 75% of the energy expenditure and pumping accounting for 18.9% [6]. Aeration systems account for the majority of WWTP energy use and are essential components of WWTPs, which highlights the need for creative approaches to increase energy efficiency in these facilities. Thus, this review focuses on the energy-intensive aspects of WWTP operations to highlight the significance of sustainable energy management techniques in terms of reducing energy costs, minimizing environmental effects, and decreasing energy consumption. Furthermore, wastewater, as a resource, presents a substantial opportunity for energy recovery in WWTPs due to its untapped energy in the form of organic matter. Wastewater potentially has high energy levels compared to the amount of energy required for its treatment. The effective tapping of this energy from wastewater suggests the possibility of converting WWTPs into energy-positive operations [7–9]. Therefore, the aim of this review is to list options for energy recovery from wastewater using technologies such as anaerobic digestion, biogas production, and advanced oxidation processes to illustrate the revolutionary effects of wastewater as a valuable energy resource in WWT processes.

Recently, a variety of techniques and technologies has been employed with the aim of maximizing energy recovery and reducing energy consumption associated with WWTPs to easily transform them into energy-positive operations. These techniques include installing heat recovery systems that can capture and utilize waste heat from treatment procedures [10] and anaerobic digestion of sludge to increase biogas production [11]. However, these techniques are required to be examined in detail to evaluate their feasibility, analyze their effects on energy efficiency and the achievement of energy-positive operations in WWTPs, and reduce their dependence on external and non-sustainable energy resources.

Several WWTPs throughout the world have made the shift to energy-positive operations with success. Advanced municipal WWTPs in Austria (Strass Treatment Plant and Wolfgangsee-Ischl Treatment Plant) as listed in Table 1, for instance, have employed energy recovery techniques and implemented biogas generation from anaerobic sludge digestion to achieve energy self-sufficiency [12]. These success stories offer motivational illustrations for sustainable energy practices to transform the energy dynamics of industrial-scale, robust, and sustainable WWTPs. Hence, the energy dynamics in WWTPs provide a special combination of difficulties and opportunities for sustainable energy management. WWTPs can be transformed from energy-neutral to energy-positive operations via energy-efficient procedures, which will eventually lower operating costs, reduce carbon footprints, and improve environmental sustainability in WWT. This review further emphasizes the significance of cutting-edge energy recovery technologies and tactics to maximize energy efficiency in WWTPs and eventually contribute to a resilient and sustainable water sector.

Table 1. Summary of wastewater and sludge treatment approaches. Reproduced with permission from Demirbas et al. (2017) [13], ©Taylor & Francis, 2017.

Treatment Type	Description	Applications
Primary Treatment	Physical separation of grit (fine, hard solids), suspended solids, and scum from the wastewater	Both domestic and industrial waste
Secondary Treatment	Biological processes like the use of activated sludge or biofilm reactors whereby biodegradable materials are removed	Mainly domestic waste
Tertiary Treatment	Advanced chemical and physical processes for nutrient removal	Both domestic and industrial waste
Sludge Treatment	Anaerobic digestion, composting, and dewatering	Sludge from all types of wastewater
Combined Treatment	Integrated systems combining multiple stages for enhanced efficiency	Complex industrial waste streams

2. Historical Context and Current Energy Practices in WWTPs

WWTPs are considered a censorious response to the growing public health concerns associated with urban sprawl and industrialization, which have led to the contamination of natural water bodies [14,15]. Traditional energy consumption patterns in WWTPs have historically been characterized by high levels of electricity and thermal energy use, mainly due to the intensive mechanical and biological processes for aeration in the activated sludge process, pumping systems, and equipment required for water treatment through the removal of solids and other contaminants to meet regulatory standards [16,17]. Research on municipal wastewater treatment plants has revealed that up to 66% of the energy used in activated sludge treatment facilities is consumed by sludge pumping and aeration, as seen in Figure 1. Reducing energy usage in these processes could lead to considerable cost savings for wastewater treatment plants [18].

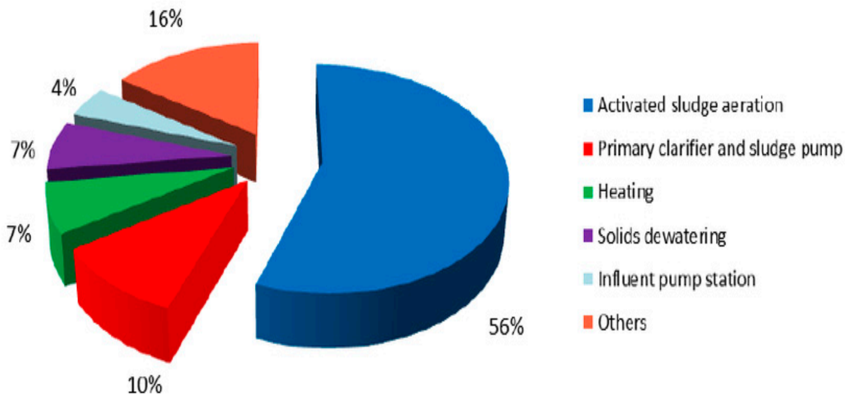

Figure 1. Breakdown of % WWTP energy usage by process. Reproduced with permission from Greg et al. (2014), ©SDEWES, 2014 (open-access conference proceeding) [18].

Initially, these facilities were focused on basic sedimentation processes to eliminate solids from wastewater. However, the emphasis shifted towards sophisticated methods of removing physical, biological, and chemical pollutants to protect water resources and comply with stringent environmental regulations as environmental awareness has increased and technology has advanced in recent times [14,19]. Today, modern WWTPs incorporate a range of processes, including primary, secondary, and tertiary treatments, along with advanced filtration and disinfection techniques [20]. The traditional energy patterns in WWT reflect an approach that is exclusively focused on meeting treatment objectives rather than energy efficiency or sustainability. The lack of emphasis on energy recovery or the integration of sustainable practices further underscores the energy-intensive nature of historical WWT operations, highlighting a critical area for improvement in the quest for highly sustainable and energy-efficient water management practices [9]. The concept of water reuse has attracted significant attention in recent years as a sustainable approach to wastewater management. Water reuse involves treating wastewater to a level that allows it to be safely used for various purposes such as agricultural irrigation and industrial processes and even as potable water after undergoing advanced purification processes [21]. As an integral part of the water cycle, wastewater should be properly managed throughout the entire water management process, including freshwater abstraction, treatment, distribution, usage, collection, post-treatment, reuse, and its final return to the environment. This practice not only helps in conserving freshwater resources but also reduces the environmental impact of wastewater discharge, as depicted in Figure 2, where municipal wastewater is a constituent in the water cycle [22]. Recent advancements in water reuse technologies have shown promising results. Membrane bioreactors (MBRs) combined with advanced oxidation processes can significantly reduce pathogens and emerging contaminants, making the treated water safe for various reuse applications. Recent studies have highlighted the effectiveness of MBRs in producing high-quality effluent suitable for reuse, with COD removal of more than 90% [21].

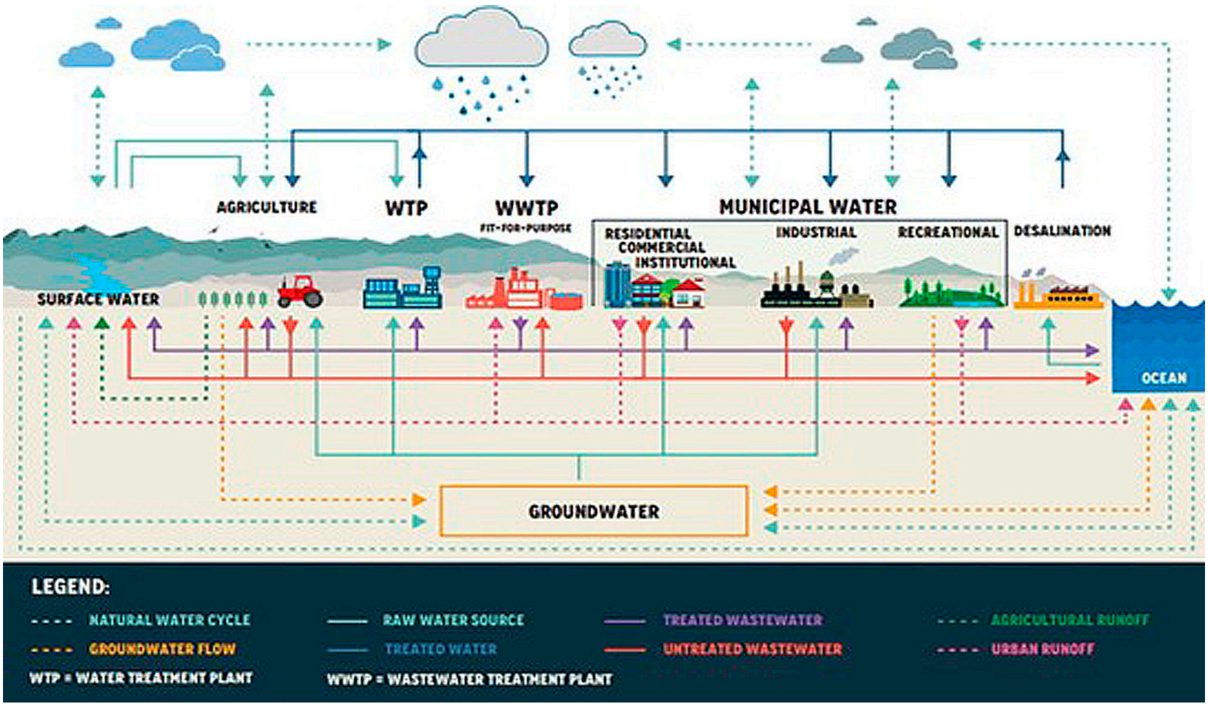

Figure 2. Illustration of wastewater in the water cycle. Reproduced with permission from the United Nations World Water Development Report (open access) [22].

In recent years, there has been a shift towards energy-efficient technologies and practices, including the recovery of resources from wastewater and the integration of renewable energy sources to mitigate the environmental and economic impacts of traditional energy consumption patterns in WWT [14,22]. Several WWT facilities in the United States of America (USA) have developed and implemented energy conservation and management plans [14] that involve the adoption of innovative technologies, such as anaerobic digestion for biogas production, thermal hydrolysis, and the integration of renewable energy sources [23]. The aim of these practices is to reduce the environmental footprint of WWT and transform these facilities from energy consumers into energy producers, highlighting a significant shift towards sustainability in the management of water resources [24]. In a WWTP, an energy energy-efficient aeration system can lead to energy reductions of 10 to 25 percent compared to traditional aeration methods [14]. These traditional WWTPs are among the largest energy consumers in municipal infrastructure, resulting in complex environmental and economic consequences [25]. WWTPs can account for up to 30% of the total operational and maintenance budget, which translates to high costs and affects the financial sustainability of these facilities, as energy is one of the largest operational expenses [14,26,27]. The pervasive nature of these costs has repercussions that ripple through the pricing structures of municipal water services, ultimately being shouldered by consumers. Furthermore, high energy usage presents a broader environmental impact due to the greenhouse gas emissions associated with electricity production from fossil fuels [28]. Carbon emissions not only exacerbate the specter of climate change but also signify a substantial ecological footprint for the sector [29]. Furthermore, aging infrastructure and increasing energy demands can lead to additional costs in terms of upgrades and maintenance to meet the energy needs of traditional WWTPs. The extensive energy demands of WWTPs tap deeply into finite resources, flagging concerns of long-term sustainability [30] with their operations focused on achieving treatment goals without significant consideration for energy efficiency. This traditional approach often results in substantial operational costs and a considerable carbon footprint due to its dependence on non-renewable energy sources [31].

2.1. Anaerobic Digestion and Biogas Production

Anaerobic digestion is a multi-stage biological process in which microbes reduce organic materials without oxygen, resulting in the formation of biogas (composed of methane, carbon dioxide, and trace amounts of other gases) and digestate [32]. The digestate is a byproduct of anaerobic digestion that contains undigested substrate; water; inorganic nutrients such as nitrogen, phosphorus, and potassium; and microbial biomass values such as soil amendments or biofertilizers [33]. Figure 3 is a schematic representation of a biogas plant (biodigester).

The principles and mechanics of anaerobic digestion involve a complex, biological breakdown of organic matter by microorganisms [34]. These biochemical mechanisms can be grouped into four transformative phases, namely as acetogenesis, acidogenesis, methanogenesis, and hydrolysis, which collectively transform complex organic substrates into simpler molecules, resulting in the generation of biogas [35]. During the hydrolysis phase, complex organic molecules like carbohydrates, fats, and proteins are broken down into simpler forms, including sugars, fatty acids, and amino acids [36]. This crucial step converts the insoluble organic material into soluble substances that can be further processed by other microbes in the subsequent stages [37]. In general, the hydrolysis process leads to acidogenesis, and its products are further reduced by acidogenic (fermentative) bacteria into volatile fatty acids (VFAs), such as butyrate, propionate, and acetate. In this process, alcohol, hydrogen, carbon dioxide, and ammonia are also produced as byproducts. This stage is characterized by the rapid growth of acidogenic bacteria that exist on the substrates produced during hydrolysis [38]. Later, acetogenic bacteria convert the remaining products of acidogenesis, particularly the VFAs (other than acetate) and alcohols, into acetic acid (acetate), hydrogen, and carbon dioxide. Acetogenesis serves as a crucial intermediary step, ensuring that the compounds are prepared for the final methanogenic bacteria. Acetic acid, hydrogen, and carbon dioxide are the primary substrates used by methanogens such as *Methanosarcina barkeri* or *Methanosaeta concilii* bacteria to produce methane after acetogenesis [39,40]. The final methanogenesis step is a process in which methanogenic archaea converts the primary products of acetogenesis into methane and carbon dioxide [41]. It occurs via two main pathways, such as *Acetoclastic methanogenesis*, in which methane is produced from the splitting of acetic acid into methane and carbon dioxide, whereas a hydrogenotrophic methanogenesis process produces methane by reducing carbon dioxide with hydrogen [42].

Although the whole digestive process relies on the activity of a diverse consortium of microorganisms through a series of biochemical reactions, factors including the type of organic feedstock, the conditions within the anaerobic digester (such as temperature, pH, organic loading rate, carbon–nitrogen ratio (C:N), presence of inhibitors, and retention time), and the specific microbial populations are critical to the optimization of this process [43,44]. Efficient digestion requires that a balanced interaction between the different microbial communities that are involved in each stage be achieved by the use of optimum operating conditions, ensuring a stable and productive anaerobic digestion process [45]. Anaerobic digestive activity leads to the generation of biogas predominantly made up of methane (CH_4) and carbon dioxide (CO_2), along with trace quantities of other gases, like ammonia (NH_3), hydrogen sulfide (H_2S), and water vapor. Methane is the main energy carrier in biogas and dictates the fuel quality and energy value of the gas, while carbon dioxide and trace gases influence its combustion properties and may require removal or treatment to meet utilization standards or to mitigate environmental impacts [46,47].

Biogas compositions are influenced primarily by the process conditions used in digestion. A wide range organic feedstock with varying biodegradability and methane potential, such as cellulose-rich materials, may result in a slower digestion process and different gas compositions [48]. The efficiency of anaerobic digestion and overall wastewater treatment is significantly influenced by organic loading and the BOD-to-COD ratio. Recent studies have shown that the BOD/COD ratio can vary significantly depending on the source of the wastewater, with food processing wastewater typically exhibiting a ratio of about 2:1, while industrial wastewater, such as that from textile production, can have much higher ratios due to the presence of non-biodegradable substances. Understanding and monitoring these parameters is crucial in optimizing treatment processes and achieving energy-positive operations in WWTPs. Optimized systems can handle higher organic loads while maintaining a BOD/COD ratio suitable for effective biogas production—often around 2:1 to 3:1 [49].

According to a recent study, typical organic load ranges for anaerobic digesters are between 1.6 and 4.8 kg COD/m^3/day. The BOD/COD ratio provides insight into the biodegradability of organic matter. A higher BOD/COD ratio (>0.5) indicates a predominance of biodegradable organic matter, facilitating efficient biological treatment. A lower ratio suggests the presence of more recalcitrant compounds that are difficult to degrade, necessitating advanced treatment processes. Studies have shown that industrial wastewater can have a BOD/COD ratio ranging from 0.1 to 1.6, with an average of 0.5, indicating varying levels of biodegradability [49].

Microorganisms also undergo thermophilic (45–80 °C) and mesophilic (25–40 °C) digestion for efficient operation at the respective temperature ranges [40], thereby influencing biogas yield and composition. Generally, bacterial populations thrive within a pH range of 6.5 to 8.0, with the most favorable conditions occurring between 6.8 and 7.2 [40], as a deviation from the optimal pH range for anaerobic digestion can hinder microbial activity, particularly that of methanogens, affecting methane production and overall biogas composition [50]. The total residence time of the substrate affects the efficiency of the process; incomplete digestion results from insufficient retention time, leading to lower methane content [44]. It can be noted that acid accumulation suppresses methanogen activity and reduces methane content, which may occur as a result of overloading, while underloading might result in low productivity [51]. Hence, an optimal C:N ratio of the feedstock (typically around 20–30:1) is required to maintain microbial health and ensure a favorable methane-to-carbon dioxide ratio [50]. Toxins, namely ammonia (NH_3), hydrogen sulfide (H_2S), and heavy metals, can also inhibit microbial activity, affecting biogas quality and quantity [52].

Although optimizing these conditions maximizes biogas yields and addresses technological considerations for anaerobic digester design and operation, enhancing the overall energy yield of the biogas [53], anaerobic digester configurations (one-stage, two-stage, or multi-stage) can enhance the operation and management of the process. Such configurations involve either the hydrolysis/acidogenesis or acetogenesis/methanogenesis phases taking place in either a single digester or separate ones, as illustrated in Figure 4. Using separate digesters makes the process more manageable and allows for the independent optimization of the operational and environmental conditions of the hydrolysis/acidogenesis and methanogenesis stages, thereby improving the overall reaction rate and biogas production [54].

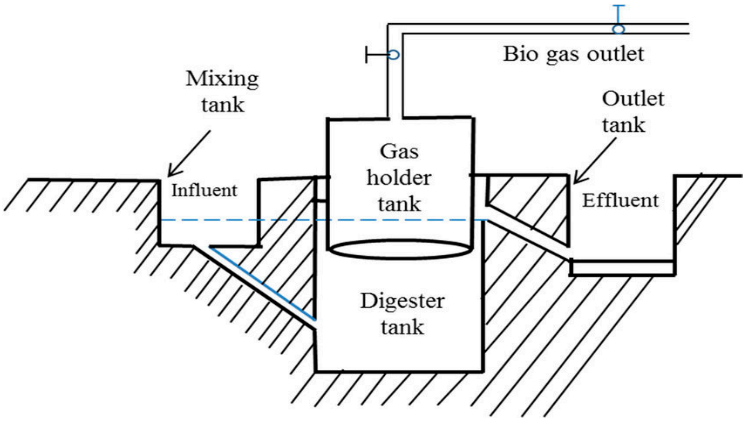

Figure 3. A schematic diagram of a biogas plant. Reproduced with permission from Rahman et al. (2017), © Semarak Ilmu Publishing, 2017, CC BY 4.0 (open access) [55].

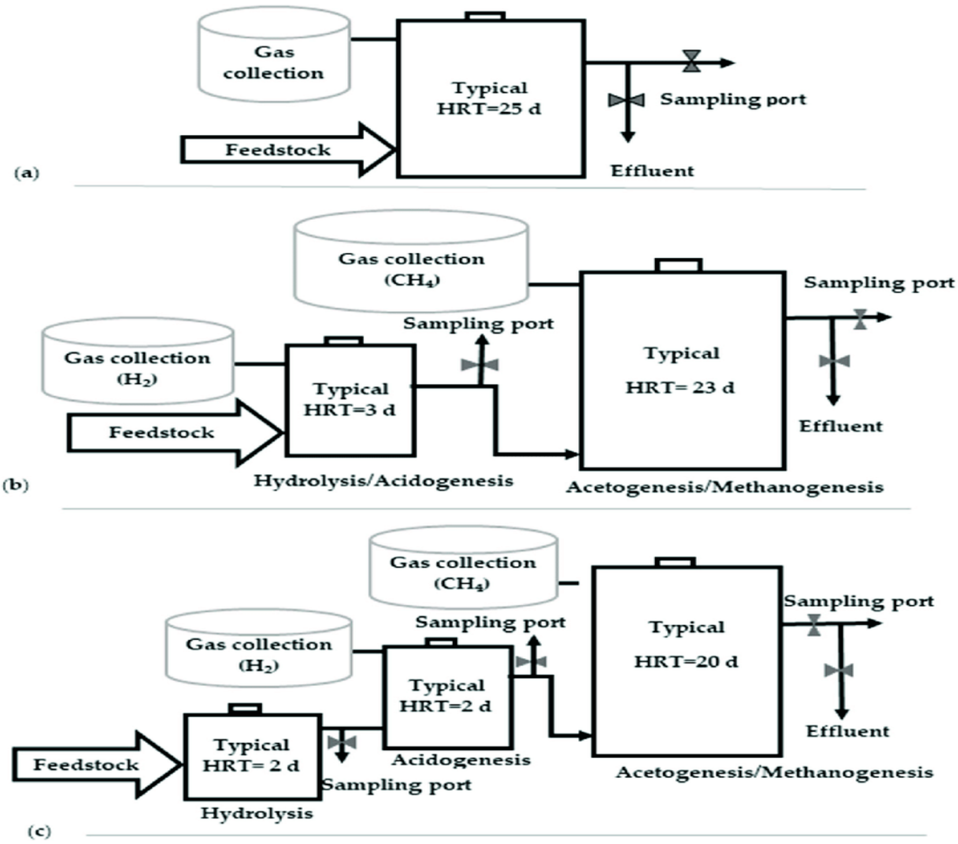

Figure 4. Types of digester configurations: (**a**) single-stage, (**b**) two-stage, and (**c**) three-stage digesters. Reproduced with permission from Rabii et al. (2019) [54], ©MDPI, 2019, CC BY 4.0 (open access).

2.2. Reduced Economic Efficiency of Biogas Stations

Biogas stations, while providing a sustainable solution for waste management and energy production, often face reduced economic efficiency due to several key factors. First, the high initial capital investment required for the construction and setup of biogas facilities, including cost-intensive anaerobic digesters and gas purification systems, poses a significant financial barrier. These costs are compounded by high ongoing operational expenses, which include maintenance, feedstock processing, and energy consumption for system operations [56].

Market prices for biogas can fluctuate based on regional supply-and-demand dynamics; thus, without favorable market conditions or supportive policy frameworks that provide financial incentives such as feed-in tariffs or tax benefits, the economic attractiveness of investing in biogas technology diminishes [57]. The economic performance of biogas stations is heavily influenced by the scale of operation. Smaller-scale plants typically exhibit lower economic efficiency due to the lack of economies of scale, which results in higher per-unit costs of biogas production. This is exacerbated by fluctuations in feedstock availability and quality, which can lead to inconsistent biogas yield and further reduce the financial returns of these facilities. Moreover, fluctuations in feedstock availability and quality can affect biogas yield and, consequently, the financial returns of biogas stations. The high costs associated with feedstock collection and transportation can also diminish overall economic efficiency [57]. To address these issues of reduced economic efficiency, biogas stations can focus on technological innovations that improve gas yield and process stability, optimize operational logistics, and reduce dependence on external energy sources. Additionally, strategic partnerships and leveraging government incentives and subsidies for renewable energy projects are crucial to overcoming financial hurdles and enhancing the overall profitability of biogas operations [56].

2.3. Harnessing Biogas for Energy

The pursuit of sustainable energy solutions has led to innovative approaches for waste management and energy production, notably through the harnessing of biogas. A solution to the global challenge of waste management is provided by the conversion of organic waste into biogas by anaerobic digestion to obtain often underutilized resources and promote a circular economy [40]. Recent advancements in anaerobic digestion have shown promising improvements in the efficiency and economic viability of biogas production. For example, a study on the application of anaerobic membrane bioreactors (AnMBRs) for swine wastewater treatment demonstrated a significant enhancement in methane yield, achieving stable COD removal rates of approximately 90% and a methane yield of 0.24 L/g-COD. The systems operated optimally, with organic loads ranging from 1.6 to 4.8 kg COD/m^3/day, and exhibited improved biodegradability, with a BOD/COD ratio of 0.5 to 0.7 [58]. Biogas is a renewable energy source that primarily consists of methane and carbon dioxide and offers great sustainability benefits. Biogas serves as an energy source for heating and electricity generation and as a substitute for natural gas [40]. Harnessing biogas for electricity and heat generation is a transformative approach to renewable energy for the seamless integration of waste management with the production of valuable resources [59].

Direct combustion is one of the oldest and most straightforward methods of harnessing the chemical energy stored in materials and converting it into thermal, mechanical, and electrical energy. Direct combustion refers to the process of generating energy by burning biomass or other fuels in a furnace or boiler to produce heat [60]. Later, this heat is used to boil water, creating steam that drives a turbine connected to an electricity generator. The journey of biogas from production to power generation begins with its extraction from digesters, followed by a cleanup and upgrading step. The lateral upgrading step is vital for eliminating impurities to increase a methane concentration that improves the calorific value of the biogas using techniques such as water scrubbing or pressure swing adsorption [61]. The direct combustion process is initiated by the ignition of purified biogas in an oxygen-rich environment (boiler or furnace), leading to a chemical oxidation reaction or the burning of methane to produce carbon dioxide, water vapor, and significant amounts of heat [62]. The heat generated from biogas combustion is used to produce steam in a boiler, where the high-pressure steam propels a turbine linked to an electrical generator, transforming thermal energy into mechanical energy and, subsequently, electrical energy [47]. Besides generating electricity, the heat produced during biogas combustion can be harnessed for heating purposes through a combined heat and power (CHP) process. Generally, CHP systems capture waste heat that would have been lost in the electricity generation process [63,64]. Later, this recovered heat is redirected for additional applications, such as heat exchangers that can capture the thermal energy to be utilized in space heating and water heating or to drive industrial processes that require thermal energy [63]. Furthermore, direct combustion is widely used in utility-scale power plants and in industrial and residential heating systems [47]. Incorporating anaerobic digesters and CHP systems in wastewater treatment plants (Figures 5 and 6) enables the effective utilization of biogas for energy production. This method produces both electricity and heat, thereby improving the overall energy efficiency of wastewater treatment plants and making them energy-positive. Adopting anaerobic digestion and CHP technology creates opportunities to substantially lower operational expenses, reduce greenhouse gas emissions, and promote sustainability by converting waste into valuable energy resources [65,66].

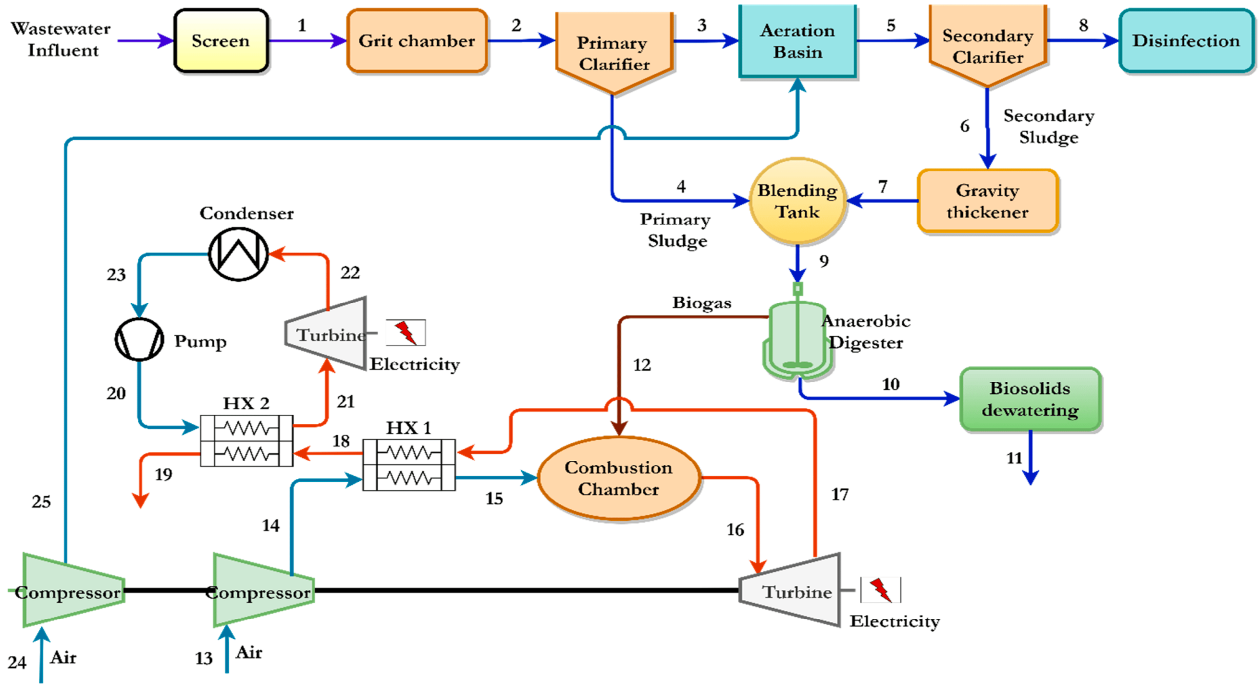

Figure 5. An energy recovery configuration for a wastewater treatment plant. Reproduced with permission from Erguvan and MacPhee (2021) [66], ©MDPI, 2021, CC BY 4.0 (open access).

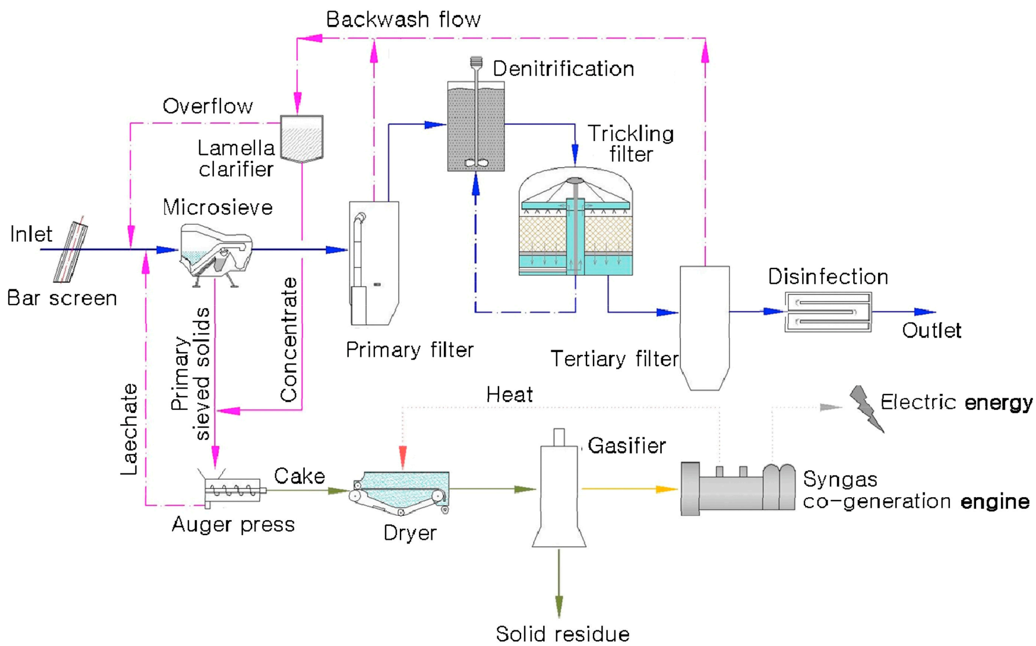

Figure 6. Energy-positive configuration of a wastewater treatment plant. Reproduced with permission from Gikas (2017) [65], ©Elsevier, 2017.

3. Biogas Upgrading Techniques and Their Efficiency

Biogas upgrading is a process of transforming biogas into biomethane, which is a renewable resource that holds immense promise for the future of sustainable energy. It is vital in refining biogas into a pure form of methane to act as a suitable substitute for natural gas, thereby tailoring biogas for uses such as injection into gas grids or as vehicle fuel [61]. Some common techniques used for biogas upgrading are membrane separation, water scrubbing, cryogenic separation, pressure swing adsorption (PSA), and chemical absorption.

3.1. Water Scrubbing

This method uses the advantage of distinct solubility levels of various biogas composition in a liquid scrubbing solution to separate and extract pure methane (CH_4) [61,67]. Physical absorption of CO_2 and other impurities from biogas is achieved using water under high pressure. The use of water as a solvent makes it environmentally friendly and cost-effective for large-scale applications. In this process, the efficiency of CO_2 removal can range between 95 and 99%) [61,68], making it a widely adopted technique. However, the process requires significant energy for water circulation and heating, which can affect its overall efficiency.

3.2. Chemical Absorption

This method uses amine-based solutions to selectively absorb CO_2 and H_2S from biogas. Chemical absorption can achieve high methane purities (>99%) [61], which makes it as an effective approach for producing biomethane with natural gas quality. However, the process involves higher operational costs and energy consumption due to the regeneration of the amine solution [67].

3.3. Pressure Swing Adsorption (PSA)

PSA separates gas species under pressure according to their molecular characteristics and affinity to adsorption materials. The core of the adsorption technique is mainly identified in porous adsorbents (zeolite, silica gel, and activated carbon) [67]. It is effective for biogas with varying compositions, offering flexibility and high methane recovery rates (95–99%) [68]. The main limitation of this method is the requirement for multiple energy-intensive adsorption and desorption cycles.

3.4. Membrane Separation

Membrane technology uses semi-permeable membranes to separate gases based on their distinct molecular size and solubility. This process is characterized by its low energy consumption and compactness, making it a suitable method for small- to medium-scale applications. Membrane systems can achieve methane purities of up to 99.5% [61]; however, their performance can be affected by gas impurities, leading to fouling of the membrane.

3.5. Cryogenic Separation

Cryogenic separation takes advantage of the different boiling points of methane and other biogas components. In this process, methane can be separated as a gas by cooling the biogas to extremely low temperatures, while other components liquefy or solidify to yield high methane purity over 97% [61] and high recovery rates. However, the high energy requirements for cooling make it less energy-efficient compared to other methods that are suitable primarily for large-scale applications where high biomethane quality is essential [67].

4. Biomethane for Grid Injection and Transportation Fuel

The utilization of biomethane as a renewable natural gas produced via the biogas upgradation processes listed in Table 2 has significant potential to contribute to the decarbonization of energy grids and the transportation sector [69]. Biomethane, through processes that can eliminate carbon dioxide and other contaminants from biogas, becomes a high-quality fuel compatible with existing natural gas infrastructure and vehicles [47]. Biomethane, whether injected into natural gas grids or used as a renewable transportation fuel, is a pivotal component in the transition towards a sustainable energy system that offers a clean, versatile, and efficient alternative to conventional fossil fuels [70].

4.1. Biomethane for Grid Injection

The injection of biomethane into the natural gas grid represents a pivotal strategy for enhancing the sustainability of energy systems. Grid injection, storage, and efficient transportation of energy help in leveraging existing infrastructure for renewable energy distribution [69]. The injection of biomethane into the natural gas grid must satisfy specific quality standards to ensure its exclusivity compared to fossil natural gas. Hence, the injection process is essential for the removal of impurities and the adjustment of calorific value [71]. The injection process is initiated with biogas upgradation to increase methane content by enhancing biogas quality to achieve high methane purity (>97%) [72]. Subsequent steps may include carbon dioxide addition to adjust the calorific value and match natural gas standards, as well as odorization for leak detection, followed by later compression and injection into the natural gas grid [73]. Grid injection of biomethane lessens reliance on fossil fuels and markedly lowers greenhouse gas emissions, supporting energy security. However, challenges include the initial investment required to upgrade facilities and regulatory and quality standard compliance to ensure a consistent supply of biogas.

4.2. Biomethane as Transport Fuel

The role of biomethane as a transportation fuel offers a promising avenue for reducing the carbon footprint of the mobility sector, particularly for heavy-duty vehicles, buses, and fleets that are challenging to convert into electrical vehicles [69]. The advantages of biomethane over conventional fossil fuels and electric vehicles include lower emissions, competitive energy density, and the utilization of existing natural gas refueling infrastructure. Biomethane can be compressed (CBM) or liquefied (LBM) to serve as a clean and efficient fuel for vehicles [74]. Its use in transportation offers a significant reduction in carbon emissions, particulate matter, and nitrogen oxides compared to diesel and gasoline. In this process, the achievement of high methane purity is essential, like in grid injection. Likewise, biomethane is compressed (CNG) or liquefied (LNG) for ease of storage and distribution [69]. Utilization of biomethane as a transportation fuel reduces environmental impacts and can offer economic benefits due to its lower operational costs [72]. However, widespread adoption faces hurdles such as the need for investment in fueling infrastructure, vehicle modifications and availability, and the scalability of biomethane production [71].

Table 2. A summary on the process approaches to the use of biogas.

Approach	Process Description	Key Advantages	Main Challenges
Direct combustion for electricity and heat	Biogas can be directly burned in boilers, engines, or turbines to generate electricity and heat, often in a combined heat and power (CHP) setup [60].	1. Efficiently produces both heat and power; 2. Reduces fossil fuel use and utilizes existing biogas without the need for extensive processing [47].	1. Biogas must be relatively clean to prevent damage to combustion equipment [75]; 2. Variability in biogas quality can affect performance [52].
Biogas upgrading	Upgraded biogas (biomethane) is injected into the natural gas grid, supplementing conventional natural gas supplies [69].	1. Leverages existing gas distribution infrastructure [76]; 2. Expands renewable energy use in the gas sector [76].	1. Must meet stringent quality standards; 2. Regulatory and technical challenges for grid compatibility [77].

Table 2. *Cont.*

Approach	Process Description	Key Advantages	Main Challenges
Biomethane for transportation fuel	Biomethane is compressed (CNG) or liquefied (LNG) to fuel vehicles, offering a cleaner alternative to diesel and gasoline.	1. Reduces transportation emissions [76]; 2. Compatible with existing CNG/LNG vehicles [78]. 3. Utilizes renewable resources.	1. Requires investment in fueling infrastructure [77]; 2. Limited vehicle compatibility and availability [78].

5. Direct Electricity Generation via Microbial Fuel Cells

A microbial fuel cell (MFC) is a device that employs microbes to catalyze the oxidation of chemicals to produce energy and electrogenesis, as shown in Figure 7. It is noteworthy that MFCs can produce voltages in the region of 0.3 to 0.7 V [79]. In contrast to a chemical fuel cell, the biofilm growth process in MFCs makes it difficult to determine the voltage generation. The identification of the maximum electromotive force (E_{emf}) of MFCs is a method of approximating the maximum voltage production [79]. The working principle, energy yields, scalability challenges, recent advancements, and certain potential applications of systems associated with MFCs are provided in this section.

Microbes such as bacteria can produce electricity by using wastewater as a source of organic matter and biodegradable substrates while also completing the biodegradation and treatment of biodegradable municipal wastewater products [80]. within microbial fuel cells (MFCs), the production of bioelectricity is facilitated by the bio-potential arising from the metabolic actions of bacteria in the anode compartment (which involves reduction processes yielding electrons and protons) and the environment that supports electron reception at the cathode, with a membrane dividing these spaces [81]. Within the anodic chamber, electrochemically active microbes have the ability to transfer electrons to an anode, where these electrons are released through the oxidation of organic and inorganic substances (serving as fuel), thereby providing a source of energy [82]. In this process, electrochemically active bacteria in the anodic compartment lead to an oxidation reaction by utilizing acetate as a fuel source [83]. Anode-respiring bacteria or electricigens/exoelectrogens are electron-donating microorganisms that are electrochemically active, whereas exoelectrotrophs are microbes that can accept electrons. A half-cell separator such as a proton exchange membrane (PEM) allows the protons produced by the electrochemically active bacteria in the anode to move into the cathode compartment. Oxygen acts as the primary oxidant in the cathode compartment and is favored for its high reduction potential and abundance. Nonetheless, the oxygen reduction reaction (ORR) stands as a significant barrier to further optimization and enhancement of MFC designs, owing to its sluggish kinetics and substantial over-potentials [82].

The highest output recorded for an MFC is 5.61 w/m^2 (11,200 $w\ m^3$), which can be contrasted with the estimated 100–150 w/m^2 national average solar power in the United States [82]. However, there are difficulties in utilizing MFCs, as the units and measurements used for energy output are inconsistent. Thus, MFC technology has emerged as one of the most significant bioenergy research hotspots in recent years, making it a viable option with the capacity to sustainably meet energy demands [81].

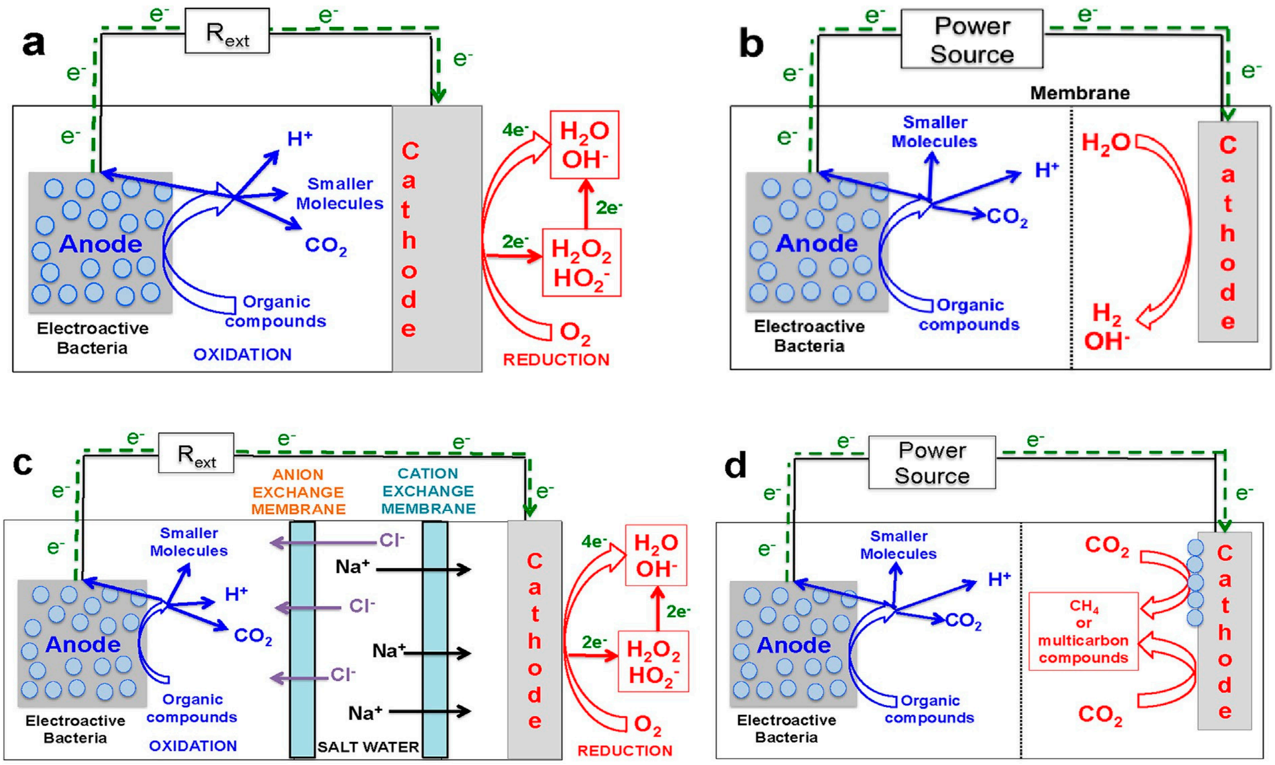

Figure 7. Schematics of a (**a**) microbial fuel cell, (**b**) microbial electrolysis cell, (**c**) microbial desalination cell, and (**d**) general microbial electrosynthesis cell. Reproduced with permission from Santoro et al. (2017) [84], ©Elsevier, 2017, CC BY 4.0 (open access).

The primary application of MFCs is in conjunction with WWT, where they can offer a workable solution to energy scarcity and water contamination challenges. It can be noted that water can become heavily contaminated due to the release and accumulation of organic materials in wastewater. In wastewater, aerobic digestion is currently a commonly utilized treatment that can effectively reduce organic contaminants into carbon dioxide through the action of microorganisms [85].

Likewise, microbes can produce a range of biofuels, volatile fatty acids, biopolymers, and other platform chemicals that are used in MFCs to generate power. Furthermore, their substrates can range from pure chemicals and organic waste to lignocellulosic biomass (LCB), as strains of MFCs have a wide range of substrate availability [86]. A major advantage of MFCs is that fuel molecules are directly converted into electricity without producing heat, which can avoid the Carnot cycle, reduce the efficiency of thermal energy conversion, and allow for higher conversion efficiencies (>70%) [87]. Despite these benefits, it has been emphasized that the scaling up of MFCs to commercial and industrial scales is severely constrained by variables related to electrochemistry, biology, economics, material science, and engineering, which depend on the design and operating circumstances of MFCs.

Advanced Oxidation Processes

One of the most effective emerging methods in wastewater treatment is advanced oxidation processes (AOPs), as shown in Figure 8. This method uses highly reactive species such as hydroxyl radicals (•OH) to oxidize and mineralize various molecular compounds [88]. This method is highly significant, as conventional WWT methods such as filtration, coagulation, and precipitation are often insufficient in removing these contaminants effectively [89]. This technique is essential for the elimination of pathogens, pharmaceutical residues, heavy metals, and organic micropollutants from the wastewater generated by distilleries, agrochemical factories, pharmaceutical companies, textile dyehouses, and other sources, as well as hazardous effluents from hospitals and slaughterhouses.

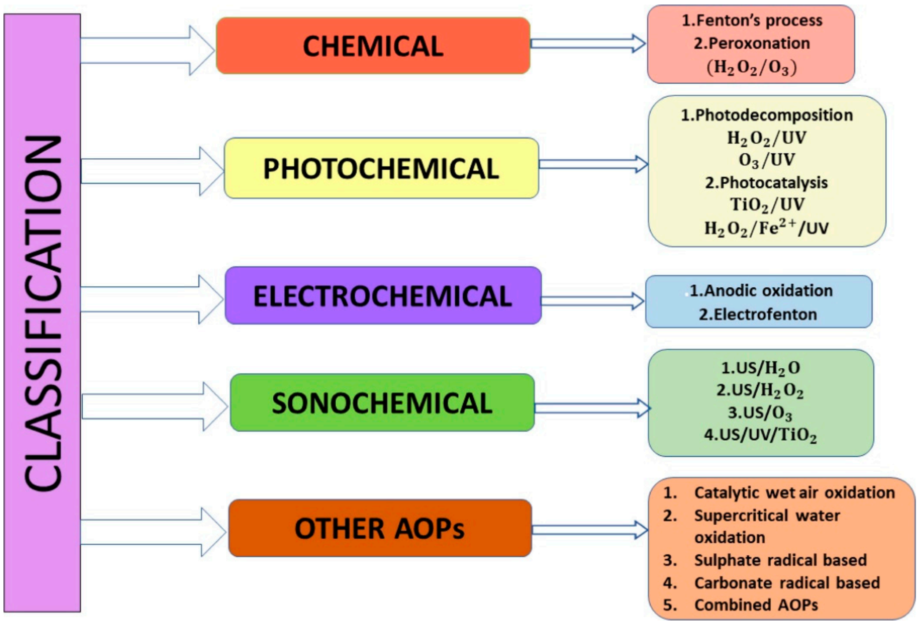

Figure 8. Classification of advanced oxidation processes. Reproduced with permission from Kumari and Kumar (2023) [90], ©Elsevier (2023), CC BY-NC-ND 4.0 (open access).

Oxidation in AOPs can be due to four main processes, namely chemical (using catalysts and chemicals), photochemical (using sunlight and sources of ultraviolet light), electrochemical (using sources of electricity), and sonochemical (using ultrasound) processes. These processes serve as the basis for the four main classifications of advanced oxidation processes. However, there have been recent advancements in these processes that have led to other types of AOPs, such as supercritical water oxidation, catalytic wet air oxidation, and processes based on carbonate and sulfur radicals. There also exist combinations of AOPs with great potency for the removal of toxins from wastewater [90].

AOPs can generate electricity or heat by using the oxidative power of reactive species such as hydroxyl radicals. M'arimi et al. (2020), for instance, analyzed the effects of sonication, ozonation, microwave, and Fenton oxidation processes on methane yield enhancement during wastewater treatment [91]. The results from the study showed that methane yield was increased by at least 15% and as much as 60% when these AOPs were applied in the pretreatment of sludge to produce biogas. The study emphasized good prospects for energy generation associated with the integration of AOPs in wastewater treatment.

In addition to improvements in resource efficiency, the integration of AOPs with energy recovery also has certain positive environmental impacts in terms of reducing dependence on conventional energy sources while minimizing waste generation. For example, ozone-based, photocatalytic (with TiO_2 for instance), and ultrasound AOPs produce few to no residuals or toxic byproducts, making them environment friendly processes. In contrast, the Fenton process produces sludge that can be further treated to produce bioenergy [92].

6. Nanotechnology in Wastewater Treatment Plants

In recent times, nanotechnology has attracted attention among researchers to be utilized in large-scale WWTPs. Westerhoff et al. (2011) demonstrated the existence and elimination of titanium in a full-scale WWTP, with an implication for titanium dioxide (TiO_2) nanomaterials. In this study, concentrations of titanium of about 181 to 1233 μg/L in raw sewage and effluent treatment of 10 representative WWTPs were evaluated. The results showed that WWTPs can remove 96% of influent titanium with 25 μg/L less effluent titanium quantity. The systematic characterization of effluents from WWTPs revealed the existence of 4–30 nm (diameter) spherical TiO_2 particles, which can be utilized for other applications [93]. Similarly, Tou et al. (2017) evaluated samples of sewage sludge in China using a sequential extraction approach coupled with single-particle inductive plasma mass spectrometry for the quantification of metallic nanoparticles. The study revealed that these sludges possess concentrations of chromium, nickel, copper, cadmium, lead, and zinc higher than values permitted by the Chinese national application standard of acid soil. The results showed that sludges contain metallic nanoparticles in concentrations of 10^7–10^{11} particles/gram, which indicates the misestimation of metal-based environmental risks as evaluated by traditional extraction approaches [94]. Likewise, Burkart et al. (2015) developed an acute toxicity analysis for *Paramecium tetraurelia* (ciliates) as a potential functional group of filter feeders and microbial predators. In this study, silver nanoparticles were selected as ion-releasing nanoparticle, and ion toxicity was evaluated. The results emphasized that ions are highly toxic, with a half maximal effective concentration (EC_{50}) of 0.73 mg/L compared to nanoparticles, with an EC_{50} of 2.15 mg/L, indicating probable risk in activated sludge [95]. Furthermore, Lazareva and Keller (2014) estimated the potential of a life cycle release model for the effective prediction of engineered nanomaterials in the environment. In this study, an environmental release model constructed with data on local differences in the consumption of products, levels of WWT, incineration of waste, and management of biosolids was utilized to estimate the release of nanomaterials from WWTPs in cities such as London (United Kingdom), New York City (United States of America), and Shanghai (China). The results revealed that analysis with a release model helps in risk assessment via the provision of approximate locations of nanomaterial discharge into aquatic systems at the local level [96]. Furthermore, Nabi et al. (2021) quantified the concentrations and size distribution of titanium dioxide and silver nanoparticles in five WWTPs in the United States. It was estimated that the titanium/niobium ratio in all the WWTP influents, effluents, and activated sludges was up to 2–12 times higher, which indicates that 49–92% of titanium is from anthropogenic sources. The results showed a titanium dioxide nanoparticle concentration of 70–670 µg/L present in influent, whereas a nanoparticle concentration of 3570–6700 µg/L of existed in activated sludge, with a 7–30 µg/L of concentration in effluent. Moreover, the overall removal efficiency of titanium dioxide nanoparticles is about 90–96%, which is higher than that of silver nanoparticles of about 82–95% [97]. However, additional investigations are required to utilize the nanoparticles from WWTPs for other applications in the future.

7. Socioeconomic and Environmental Implications

Initiatives for energy recovery are essential for tackling the escalating challenges of resource depletion, climate change, and expanding energy expenses. The socioeconomic and environmental effects of energy recovery are examined in this paper, with an emphasis on financial savings, a smaller carbon footprint, and community involvement.

7.1. Economic Savings from Energy Recovery

The potential financial savings that energy recovery provides is one of its main benefits. Businesses and industries could recover and repurpose waste energy, which reduces operating costs and decreases dependence on outside energy sources. The economic feasibility of waste heat recovery systems in industrial operations was examined, highlighting the beneficial effect on the bottom lines of organizations [98].

7.2. Reduced Carbon Footprint and Environmental Benefits

Initiatives for energy recovery lower the overall carbon footprint, which has a major positive impact on environmental sustainability. Utilization of recovered energy can assist in replacing traditional energy sources that are linked to significant carbon emissions, especially when the energy is from renewable sources. The significance of sustainable energy practices in accomplishing global climate goals and reducing the impacts of climate change is emphasized by studies conducted by the IPCC (Intergovernmental Panel on Climate Change) [99].

7.3. Community Engagement and Perception

Positive perception and community involvement are essential for the success of any energy recovery project. It can be ensured that locals are aware of the advantages of energy recovery by interacting with them in public fora, informational campaigns, and participatory decision-making processes. The significance of community involvement in the promotion of sustainable energy transitions was highlighted in recent investigations, revealing enhanced public support and perception [99].

Thus, energy recovery programs are a viable solution for the challenges related to the economy and environment. Further, organizations can reduce both their carbon emissions and costs via the capture and reuse of wasted energy. Successful community participation is essential to the success of these programs, as open communication of wider advantages is guaranteed, and support from the local population can be built. Energy recovery becomes apparent as a crucial element in the development of a robust and environmentally sensitive future, as there is a potential need for sustainable energy alternatives.

8. Associated WWTP Application Challenges and Solutions

In real applications targeted at meeting the needs of an increasing population, along with more stringent regulations governing water quality and discharge standards, the energy needs of WWTPs are projected to rise. According to recent research, the energy used by WWTPs makes up around 20% of the entire energy used by municipalities [65].

The possibility of energy self-sufficient WWTPs has drawn increasing attention from researchers and innovators due rising energy costs and environmental concerns. Energy-self-sufficient WWTPs are those that obtain all the energy needed to run their operations from the energy contained in the wastewater and water they treat, without the need for outside energy sources [5]. To achieve energy self-sufficiency in WWTPs, the following two complementary factors are needed:

(1) Energy savings through increased process efficiency in individual units: Increasing the efficiency of individual processes within WWTPs is critical to reducing overall energy consumption. Optimizing biological treatment processes, improving aeration systems, and integrating advanced monitoring and control systems have been looked at in recent research [5].

Saving energy in the aeration process contributes to savings in overall energy consumption of the WWTP. Modern techniques such as the use of fine bubble diffusers and the implementation of high-efficiency blowers can substantially reduce energy consumption. Studies have shown that switching to more efficient aeration technologies can save up to 50% of the energy used in this process [65].

The integration of real-time monitoring and control systems allows for the dynamic adjustment of process parameters, ensuring optimal operation at all times. For example, the use of dissolved oxygen control systems in the activated sludge process can lead to significant energy savings [100]. Additionally, implementing machine learning algorithms to predict and adjust operational conditions can further enhance efficiency [101].

Optimizing the biological treatment process, such as by using enhanced biological phosphorus removal (EBPR) and anaerobic ammonium oxidation (ANAMMOX), can reduce the energy required for nutrient removal. These processes are more efficient and can lead to lower operational costs while maintaining high treatment standards [102].

(2) The extraction of energy from renewable and/or underutilized sources such as chemical and thermal energy that are present in WWTPs: Harnessing renewable and underutilized energy sources within WWTPs can significantly contribute to the achievement of energy self-sufficiency. This involves capturing and utilizing biogas, integrating CHP systems, and recovering thermal energy [5].

Anaerobic digestion of sludge produces biogas, which can be used to generate electricity and heat through CHP systems. Modern WWTPs are increasingly adopting this technology, with some plants achieving net-zero energy status by fully utilizing the produced biogas. Recent publications have highlighted efficiency improvements in biogas production through co-digestion with other organic waste, which increases biogas yield and energy recovery [65].

CHP systems efficiently convert biogas into electricity and thermal energy, which can be used to heat the digesters and for other plant operations. Integrating CHP systems into WWTPs has been shown to improve overall energy efficiency and reduce reliance on external energy sources. Recent case studies have demonstrated that well-designed CHP systems can cover a significant portion of a plant's energy demand [64].

Recovering thermal energy from wastewater and sludge can provide a substantial energy source. Technologies such as heat pumps and heat exchangers can extract thermal energy from effluents, which can then be used to preheat incoming wastewater or for other heating requirements within the plant. This approach not only saves energy but also improves the overall sustainability of the treatment process [64].

9. Future Prospective

In energy recovery from WWTPs, advancement in technology is a significant factor that needs to be considered. New technological innovations could help to minimize the consumption of energy while enhancing resource recovery, which can be performed by optimizing treatment techniques for efficiently utilizing energy and chemicals. Improvements in WWTPs will contribute to carbon neutrality goals in the context of the global circular economy [103]. Traditional approaches to WWT have been established over a long period time, including the active sludge method whereby filters are trickled, anaerobic processes, oxidation processes, and membrane treatment processes. Hence, the application of catalysts to develop catalytic ozonation processes could minimize the utilization of chemicals and energy to reduce energy consumption in these conventional techniques [104]. Membrane process advancements should prioritize strategies for membrane fouling reduction, such as enhancing membrane materials and operational methods to enhance energy efficiency [103]. Furthermore, emerging innovations have been developed to minimize WWTP challenges [105]. A significant development in the traditional anaerobic digestion process is the application of combined heat and power systems, which produces electricity and heat by consuming biogas. It has been reported that this technique could yield 75% 350 kWh of electricity per million gallons of treated wastewater [105]. It was predicted in a recent study that a decrement of 26% of statewide power consumption in the treatment of wastewater in Texas can be obtained if all WWTPs implement CHPs [106]. Moreover, Escapa et al. (2016) developed microbial electrolysis cell technology to transform organic matter in wastewater directly into hydrogen gas to reduce energy during the treatment of wastewater. In this technique, an electrochemical reaction occurs with the microorganisms on the anodic side of the cell to enable electron transfer to a solid electrode from a biodegradable substrate. A suitable anode, cathode, and membrane are required to develop a microbial electrolysis cell (MEC). These materials should possess good conductivity, stability (chemical, physical, and biological), and a large surface area and be economically feasible. The study revealed that an MEC is a robust process that can help to achieve a 75% reduction in chemical oxygen demand associated with the consumption of energy [107]. Biosolid incineration systems and effluent hydropower systems are other innovative techniques that have been introduced in recent years to reduce energy in WWTPs.

Traditionally, most municipal WWT facilities primarily focus on the treatment of wastewater and releasing it into the environment. In recent years, there has been a particular emphasis on developing innovative methods to supply water, energy, and raw materials such as nutrients or organic substances for recycling, reuse, and recovery techniques. Policy frameworks have been developed across the world to encourage the recovery of energy from wastewater. According to the European Commission, in 2022, there was a scaling down of the consumption of energy during WWT in an effort to reduce the amount of micropollutants from large-scale industries [108]. According to the zero-waste program of Europe established in 2014, there is a need to enhance energy recuperation through methods such as waste-to-energy conversion and the utilization of biofuels [108]. Likewise, the Paris Climate Agreement has increased the necessity of energy recovery in WWTPs. Recently, there has been a significant focus on utilizing wastewater as an asset for the production of biofuels like biomethane, essential nutrients like nitrogen and phosphorus, materials for manufacturing such as bioplastics and cellulose fiber, and other valuable commodities [109]. The second circular economy action plan launched in 2020 is set to provide support for upcoming revisions of the National Energy and Climate Plans and climate policy in several countries. In addition, several countries proposed the Integrated Nutrient Management Action Plan (INMAP) to encourage sustainable nutrient use and recovery from waste (wastewater and all other types of waste) [110]. Thus, the recovery of energy from wastewater is set to increase in the future with all these policy frameworks.

WWTPs play an essential role in the circular economy and sustainable water management. Generally, treated wastewater can serve as a source of potable water for domestic and utility use. Hence, WWTPs are known to be one way of providing an alternate solution to inadequate water supply in certain dry areas and industries. Nutrients contained in wastewater are beneficial to agriculture, as they can function as fertilizers. The measurement of wastewater treatment systems' efficiency helps to discover areas that enhance system effectiveness to assure long-term viability. Hernández-Chover et al. (2023) developed an efficiency model to promote the sustainability of WWTPs. Results from the model indicated that the majority of plants can effectively eliminate a greater amount of wastewater contaminants, which can be converted into valuable energy and recycled water, leading to increased resource generation for society [111]. Further, Castellet-Viciano et al. (2022) reported that most literature focuses on the recovery of energy and nutrients gained from WWTPs and their benefit in the circular economy. Moreover, less attention is directed towards asset management, which helps to fulfill the goals of the circular economy without the need for modern technology. Specifically, the study identified that non-optimal property management procedures can decrease the lifespan of equipment by two to three years due to its impact on other factors. The results suggest that the implementation of efficient maintenance procedures could reduce environmental effects by 15.39% to 25.01%. The magnitude of environmental effects might increase by a factor of a thousand, considering the abundance of this type of technology in both wastewater and water facilities [112].

A new framework called water in circular economy and resilience (WICER) was developed to provide solutions associated with water pollution and challenges in the urban sector by offering a comprehensive and innovative method for wastewater treatment to provide sustainable, inclusive, and efficient water supply services. Hence, the WICER framework is predicted to provide sustainable and accessible services, eliminate waste and pollution through design, and conserve and restore natural systems [113].

10. Conclusions

This review emphasizes the significance of WWTPs for resource recovery and environmental preservation while also accentuating the difficulty of balancing the energy intensity of these facilities with the need for efficient removal of pollution. It also illustrates the ability of WWTPs to achieve energy-positive status and drastically lower their energy usage by implementing cutting-edge energy recovery technologies and management techniques. Furthermore, effective case studies included in this review provide a road map for future developments by demonstrating the usefulness and advantages of practical policies. Furthermore, this article lists current policy frameworks and technology advancements that can facilitate the shift to highly energy-efficient and sustainable WWTP operations, thereby advancing the general objectives of carbon neutrality and a circular economy.

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