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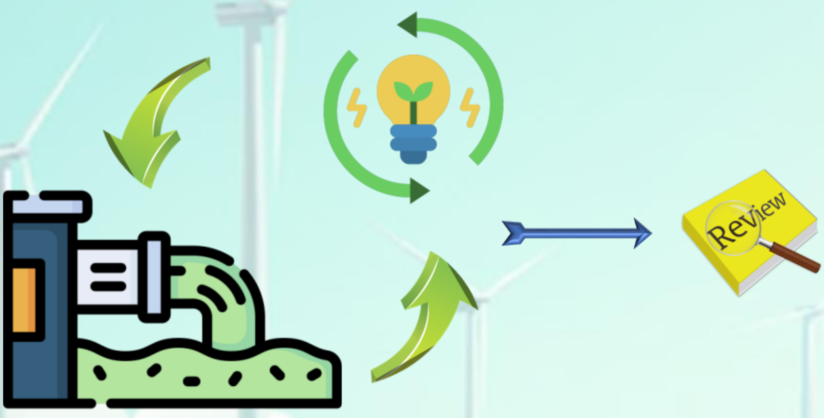
Using Wastewater for Green Energy Production: A Review

Marzie Razavi

Highlights

- Utilizing wastewater as an energy source.
- Generating bioelectricity through microorganisms in biomass.
- Reducing energy reliance and cutting wastewater treatment plant costs.
- Using green energy sources, including agricultural, industrial, and domestic wastewater.

Graphical Abstract



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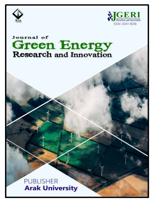

Using Wastewater for Green Energy Production: A Review

Marzie Razavi *

Department of Civil Engineering, Tafresh University, 39518-79611, Tafresh, Iran.

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* ***Corresponding author***
E-mail address:
m.razavi@tafreshu.ac.ir (M. Razavi)

A B S T R A C T

As oil resources become increasingly scarce, the need to transition to renewable energy sources is critical for sustainable living. The United Nations first emphasized the importance of sustainable development in 1987, highlighting the "central role" of energy in this effort. After years of research, innovative solutions for sustainable energy have emerged, with energy production from wastewater showing significant potential. Wastewater can be converted into biogas through anaerobic digestion, where microorganisms break down organic matter in the absence of oxygen to produce methane, which can be used for electricity, heat, or fuel. This process not only aids in reducing greenhouse gas emissions but also supports environmental protection and waste management. The growing demand for renewable energy has sparked significant interest in these techniques, which utilize bacteria to generate electricity, further demonstrating the potential of wastewater as a sustainable energy source. Using wastewater for energy not only lowers operational costs but also allows treatment plants to generate energy on-site, reducing reliance on external energy sources and lowering carbon emissions. Exploring these renewable energy sources is crucial, particularly given the large volumes of wastewater generated from agricultural, industrial, and domestic activities. This paper reviews the potential of wastewater as a green energy source, discussing specific technologies for treating various wastewater types and the associated challenges and opportunities. By examining successful case studies and emerging trends, it aims to advance green energy solutions that promote both environmental sustainability and economic growth.

1. Introduction

Non-renewable natural resources, such as oil, will end in the coming years, and therefore, humans must move towards the use of renewable energies to provide their energy needs. It seems that energy supply methods that do not require fossil fuel sources can be classified as sustainable energy [1]. The concept of sustainable development was officially introduced by the United Nations in 1987, where the significant role of energy in achieving sustainable development was acknowledged [2]. Today, researchers around the world are engaged in creating different solutions for sustainable energy production, which leads to the identification of different innovative approaches for green energy production. In this context, utilizing wastewater as a raw material for energy generation has garnered considerable interest [3,4]. Sustainable energy is energy that is produced and used in a way that "satisfies present human needs without hindering the capacity of future generations to satisfy their own needs". One of these methods is using wastewater and turning it into biogas and then producing energy from it. This method, known as green energy production, uses waste materials to produce energy and reduces greenhouse gas emissions.

In other words, in order to produce green energy from wastewater, environmentally friendly methods should be used [5,6]. The increasing energy demand highlights many concerns regarding environmental protection. Therefore, there is a need to develop and expand various clean and sustainable energy production technologies. Today, the use of wastewater as a source of energy production is viewed from a new perspective. In fact, using this method, waste materials and garbage become a valuable resource for energy production [7,8]. One of the newest methods of generating electricity is the use of microorganisms in biomass, which is also called bioelectricity production. In 1911, Potter made the first observation and discovery of the flow of electricity [9]. At that time, his work did not receive a special response, but in recent years, the ability of bacteria to produce energy has been discussed again. It seems that the need for renewable and new energy sources is one of the reasons for this return. In this method, the conversion of wastewater into biogas is generally done through anaerobic digestion and microorganisms decompose organic matter in the absence of oxygen [10].

Methane, which is the major part of the produced biogas, is used to generate electricity, heat or as a fuel. In addition to utilizing renewable and cost-effective energy sources, this method plays a crucial role in waste management, environmental protection, and the conservation of natural resources. It helps reduce the harmful environmental impacts of pollutants, supports green energy production, and contributes to enhancing the beauty of the landscape. Using the potential of wastewater reduces the harmful environmental effects of pollutants and produces green energy. The use of this method reduces the operational costs and also the energy produced in the treatment plant can be used in the facilities of the same place and eliminates the need to receive energy from external sources [11,12]. Also, this strategy is a means to compensate for energy consumption in sewage treatment plants and leads to the reduction of carbon emissions in the environment [11]. Considering that sustainable energy production from wastewater requires the use of new and advanced, cost-effective and scalable technologies, therefore there is a need to investigate and collect accurate and complete information in this field. Since all agricultural, industrial and domestic activities produce large amounts of wastewater, the need to investigate these rich and unique sources for green energy production is well felt. The purpose of this paper is to examine the diverse potential of wastewater as a source of green energy, along with the available technologies for treating different types of wastewaters—urban, industrial, and agricultural—while addressing their specific challenges and opportunities. In addition, various methods to convert these wastes into green energy will be investigated. This paper provides a comprehensive overview by showing successful case studies, advanced technologies and emerging trends. Comprehensive research, innovation and implementation in this critical area will help advance green energy generation solutions, thereby promoting environmental sustainability and supporting economic growth.

2. Wastewater Types and their Characteristics

All living organisms excrete waste materials from their bodies daily. In addition, industries, factories and agricultural activities also discharge amounts of waste materials into the environment every day. These waters are mainly known as sewage and have different quantitative and qualitative characteristics. Therefore, it is necessary to know the characteristics of different wastewater types in order to perform successful purification processes and generate energy from them. Table 1 generally lists some kinds of wastewater that are utilized to produce energy.

Domestic Sewage: Domestic sewage mainly includes human excreta, toilet waste, washing detergents and food residues [13,14]. According to the characteristics of domestic sewage, including the presence of organic materials for decomposition by bacteria, it has been used to produce different forms of renewable energy. Many researchers have achieved successful results in this field. For example, in 2011, Puig et al succeeded in purifying wastewater and simultaneously producing electricity using microbial fuel cell technology. In this study, which was conducted on a laboratory scale with a focus on the removal of organic matter and energy production, the testers succeeded in removing 80% of organic matter and producing 1.44 watts per cubic meter [15]. Table 2 presents the various compounds found in domestic wastewater.

Agriculture Wastewater: The wastewater generated in agriculture contains large organic loads, nutrients and pollutants. It usually contains high nitrogen and phosphorus which can cause eutrophication in water bodies when were not treated properly. Agricultural wastewater has always been a high BOD, COD waste water quality is good enough to be used as bio energy production.

Industrial Wastewater: Industrial wastewater varies widely depending on the industry [17,18]. There is a wide range of impurities in it, heavy metals, organic substances and inorganic compounds [19]. The high degree and diversity in the structure of industrial wastewaters require methods for specific treatment that can use their energy potential efficiently.

Domestic Wastewater: The main components of domestic or municipal sewage are organic household wastes, including human waste, food remains, soaps, and detergents [13,14]. Domestic wastewater represents a steady supply of organic matter that can be converted into biogas or any other renewable energy by means of anaerobic digestion.

Agriculture Runoff: This would refer to water that spills over from agricultural land during rainfall or irrigation [20]. This runoff often picks up soil, fertilizers, pesticides, and other chemicals used in farming.

Table 1. Wastewater Types

Domestic wastewater
Industrial wastewater
Septic tank wastewater
Leachate
Agricultural runoff
Urban runoff

Table 2. Domestic wastewater components [16].

Microorganisms	Pathogenic bacteria, virus and worm's egg
Biodegradable organic materials	Oxygen depletion in rivers, lakes and fjords
Other organic material	Detergents, pesticides, fat, oil and grease, color, solvents, phenols, cyanide
Nutrients	Nitrogen, phosphorus, ammonium
Metals	Hg, Pb, Cd, Cr, Cu, Ni
Other inorganic material	Acids, for example hydrogen sulphide, bases

Runoff water often carries organic materials and nutrients from fertilizers, which can promote the growth of biomass in water bodies. This biomass, like algae, has been shown to be useful in being harvested and processed into biofuels by means of anaerobic digestion or fermentation [21]. This will give room for the production of green energy while managing nutrient pollution in water bodies.

Sewage Sludge: The semi-liquid by-product from treatment processes of wastewater that is generally further treated in an anaerobic digester, in which microorganisms break down organic matter in an oxygen-free environment to form biogas, largely composed of methane, used to run electricity, provide heat, or as biofuel in vehicles. Anaerobic digestion not only helps to produce renewable and cleaner energy [22] but also decreases the sludge volume while producing a nutrient-rich digestate for fertilizer applications.

3. Technologies for Green Energy Production

Anaerobic Digestion: Anaerobic digestion is one of the most studied and applied methods in the conversion of organic matter existing in wastewater into biogas. The final product consists basically of methane and carbon dioxide [23-28]. Simply, it involves a series of processes mediated by microbes: hydrolysis, acidogenesis, acetogenesis, and lastly, methanogenesis [29,30]. The produced methane could be utilized for electricity generation, heating, or even as a form of fuel for vehicles. Anaerobic digestion is a process whereby microorganisms break down organic matter in wastewater in the absence of oxygen, to yield biogas. This technology manages organic waste and recovers valuable energy, hence minimizing over-reliance on non-renewable resources. A number of studies have documented successful cases of WTE projects implemented around the world, covering different technologies and their efficacy in producing green energy. Gu et al. (2017) evaluated the possibility of WWTPs being energy self-sufficient and the challenges to be anticipated in such a scenario. They talked about integrating anaerobic digestion for the production of biogas from sewage sludge and its subsequent electricity and heat generation, touting huge reductions in the energy consumed by the plant [31]. WWTPs may be empowered with the potential to anaerobically digest organic matter in wastewater into biogas, mainly methane and carbon dioxide. This captured biogas can be put to use as a renewable energy supply in power and heat generation, hence reducing dependence on fossil fuels. Advanced treatment processes recover valuable nutrients such as nitrogen and phosphorus from wastewater for fertilizers. Modern WWTPs are designed to be energy-efficient, including technologies such as combined heat and power systems and energy-efficient pumps and motors. This contributes greatly to reducing the overall energy use and carbon footprint of a treatment process.

Microbial Fuel Cells (MFCs): MFCs harness electricity generation through bacteria involved in the metabolic activities directly converting organic matter present in wastewater into electricity [32]. The idea of bioelectricity production by MFC, initially discovered in 1911. The anodic chamber hosts bacteria that oxidize organic matter to release electrons, which then transit to the cathode through an external circuit and in the process generate electricity [33]. The benefits of using MFCs have thus far been wastewater treatment and power generation. It provides opportunities for continuous electricity generation through microbial activities, and potential uses of MFCs have been for in situ wastewater treatment systems that allow simultaneous pollutant removals with energy recovery [8]. There is ongoing work related to the development of MFCs in a way that allows performance improvement and the scaling up of the devices for real-life applications [34]. As stated above, Microbial Fuel Cells are an emerging means for producing electrical energy directly from organic matter in wastewater through the metabolism of microorganisms. This directly removes the requirement of an outside carbon-source that will provide energy along with the carbon footprints associated with energy generation. Generally; a lot of methane and carbon dioxide are said to be generated as a result of wastewater treatment. In contrast to other methods, where organic matter is directly converted into electricity in MFCs, there is a significantly lower release of methane. As a result, this process produces a reduced amount of greenhouse gases, contributing to a lesser overall impact on climate change. FCs work at ambient temperatures and pressures, which are low and do not utilize much energy input than conventional treatment. This further reduces the carbon print of the wastewater treatment process. MFCs have great potential and effectiveness in the degradation of a wide range of organic pollutants even for such which are less biodegradable in the conventional treatment process. This leads to better quality effluent water and less pollution in the receiving water body. There can be scaling of MFCs for different sizes of operations: small, on-site treatment systems or large municipal plants. It can serve its purpose with much flexibility for adoption and cumulative impact toward pollution reduction and the carbon footprint. MFCs have gained a lot of interest because they are able to generate electricity from wastewater. Electricity was also generated through MFCs employing floating air cathodes, hence proving the potential applicability of the technology [35]. Similarly, the activity of various inoculums was tested in urine-fed MFCs, which were monitored for power performance and microbial community dynamics. This study further demonstrated the adaptability and efficiency of MFCs in converting waste into electrical energy [36]. In the recent past, the electrochemical system has continuously improved and evolved with the development of new materials and better electrode configuration that leads to better performance of the microbial fuel cells. The use of nanomaterials and conductive polymer innovations has developed that offers increased power output and efficiency in treating wastewater. According to the study made by Mook et al. on 2014, electrochemical systems for wastewater treatments are combined or integrated with renewable sources of energy. One such approach focuses on the use of solar, wind, and bioenergy to power electrochemical processes for bettering wastewater treatment efficiency and sustainability. In this vein, this review presents an overview of the many technologies involved, advantages, challenges, and prospects of this area and underlines that renewable energy will play a key role in developing cost-effective and environmentally benign wastewater treatment solutions [37].

Algal Biofuel Production: Algal cultivation is particularly suited to nutrient-rich wastewater, which offers a combination of essential organic and inorganic nutrients. The biomass generated from algal growth can be harvested and further processed into various biofuels such as biodiesel, bioethanol, and biogas. Due to the high yields of algal biofuels and their ability to grow on non-agricultural land, they are considered one of the more sustainable renewable energy options. This method presents a promising avenue for renewable energy production [38]. Another well-established route is biogas production through anaerobic digestion (AD), which converts organic matter into biogas. Researchers have explored ways in which wastewater treatment plants (WWTPs) can achieve energy neutrality by optimizing energy recovery from internal sources, such as producing biogas from sewage sludge [39]. This approach not only aids in waste management but also helps reduce the energy footprint of WWTPs [40,41]. Additionally, studies have investigated the potential for increasing renewable energy use in WWTPs by examining the efficiency of biogas production through co-digestion processes that involve sewage sludge combined with other organic wastes[42]. This paper discusses the practical challenges and solutions for achieving energy self-sufficiency at wastewater treatment facilities.

Hydrothermal Carbonization: Hydrothermal carbonization is a kind of thermo-chemical process that allows the conversion of wet biomass under high pressure and moderate temperature into a carbon-rich solid called hydrochar. The technique finds its application mainly in the treatment of high moisture wastewater and for producing solid biofuels suitable for energy production. HTC offers an avenue to transform wet biomass into a possibly useful, reliable energy source—a term quite relevant in securing sustainable waste management and renewable energy generation. A 2024 article by Ho et al. discussed the challenges and innovations of HTC on the conversion of high-moisture waste into biofuels [43]. They investigated the feasibility of applying such a method from the laboratory scale up to real-scale application. This emphasized the environmental and economic benefits by upgrading the process. In research conducted by Gonzalez et al. in 2022, a comprehensive review of the parameters affecting HTC and its application in increasing the energy potential of biomass has been done. This paper describes how HTC can improve the properties of various biomass feedstocks for use as biofuels and other renewable energy sources [44].

Photocatalytic hydrogen generation: Photocatalytic production of hydrogen with wastewater is another prospective technique that dominates renewable energy generation coupled with environmental remediation. This process generates clean hydrogen fuel while treating wastewater by utilizing the organic pollutants present in wastewater and therefore contributes to the goals of sustainable energy with reduced pollution. Further research and development should be focused on the optimization and commercialization of large-scale processes. Zhang et al. provided an extensive review of photocatalyst materials and techniques for enhancing the efficiency of hydrogen production, along with thorough explanations of the underlying mechanisms and the challenges associated with this field [45]. According to a review by Penn et al. in 2020, photocatalytic hydrogen evolution is among the clean routes for solar energy conversion into hydrogen, suffering from inefficiencies in light absorption, carrier separation, and surface reactions [46].

Integration of membrane bioreactors: Membrane bioreactors (MBRs) represent the coupling of biological treatment and membrane filtration, therefore capable of providing high-efficiency wastewater treatment together with biogas production. Coupling MBRs with anaerobic digestion processes improves pollutant removal and enhances biogas production for optimal treatment and energy recovery. Neo et al. proved in 2016 that integrated MBR has future prospects to be a potential technology in treating wastewater and reducing its pollution, above all for the creation of new sources of energy and nutrients. They also showed that integrated MBR makes energy and nutrient recovery environmentally and economically feasible [47]. In 2020, Kalassov et al showed that classical technologies for gas processing in biofuel production are economically inefficient and lead to burning biogas for energy. Integrating biological gas production with membrane separation improves CO_2 emission elimination. MBRs offer environmental and economic advantages such as energy savings, low cost, less space occupation, and operational flexibility that make them ideal for biogas production [48].

Hybrid Systems: The combination of different technologies mentioned as hybrid systems can cause maximum energy recovery from wastewater. These systems are designed for repeated wastewater treatment and lead to increased energy production as well as treatment efficiency.

4. Future Challenges and Guidelines

Such potential for energy production from wastewater encounters a myriad of challenges: technical difficulties, high upfront costs, requires specialized maintenance and operation, variability in the composition of wastewater, and finally, complex regulatory frameworks. Another big barrier is the public resistance to health and safety concerns. This resource, however, is maximally exploited through technological development, integrated systems, public awareness, optimization of the wastewater streams, Business models yang sustainable, and international collaboration. Comprehensive life cycle assessments may further guide improvements and policy decisions to ultimately make the use of wastewater for energy production a prominent contributor to both sustainable development and environmental protection.

Technical Challenges: The diverse composition of wastewater presents significant challenges for sustainable energy production. The development of robust and adaptable technologies capable of managing diverse wastewater streams is crucial for their widespread adoption. Ensuring consistent performance across different wastewater types requires continuous innovation and optimization.

Economic Considerations: The initial investment required for establishing wastewater-to-energy systems can be substantial. However, the long-term benefits, including energy savings and reduced waste disposal costs, can offset these initial expenditures. Policies and incentives are necessary to support these investments and encourage the adoption of such technologies.

Environmental Effects: While wastewater-to-energy technologies offer significant environmental benefits, such as reduced greenhouse gas emissions and decreased water pollution, careful management is required to prevent potential negative impacts, such as the release of harmful by-products. Ensuring proper operation and monitoring of these systems is crucial to maximize their positive environmental contributions.

Research and Development: Continued research and development are vital for improving the efficiency and scalability of these technologies. Innovations in biotechnology, materials science, and process engineering will play a crucial role in overcoming current limitations and fully harnessing the potential of wastewater for green energy production. Investing in R&D will be key to advancing this field and achieving broader implementation.

5. Conclusions

Non-renewable natural resources will definitely run out, so there must be a reliance on renewable energy sources to supply human needs with energy in a sustainable manner. The increasing energy demand from all over the world accentuates the need for clean and sustainable technologies in this sector. Wastewater, once viewed merely as discharge waste, is now recognized as a valuable resource for energy production. The generation of bioelectricity by microorganisms present in biomass has regained attention as humanity continues its pursuit of renewable energy sources. This production of energy from wastewater decreases the cost of operation and lessens overdependence on an external source of energy, especially in treatment plants. The process offsets the energy used by sewage plants. However, this low carbon energy attainment from wastewater requires new advanced and affordable yet scalable technologies. It, therefore, calls for detailed research accompanied by accurate data collection. Given large volumes of wastewater originating from agricultural, industrial, and domestic activities, there is a need to exploit these rich sources of green energy production. This paper reviews the potential of wastewater as a green energy source through looking at various treatment technologies of wastewater and discussing associated challenges and opportunities. The paper discusses successful case studies, advanced technologies, and emerging trends to drive research, innovation, and the implementation of green energy solutions, all with the goal of promoting environmental sustainability and economic growth. It also aims to introduce several methods of producing cost-effective and readily available energy, commonly referred to as renewable or green energy.

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Declaration of competing interest

The author declares that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, have been completely observed by the author.

Bibliography

Marzie Razavi obtained her M.Sc. degree in Environmental Engineering from Iran University of Science and Technology (IUST), Tehran, Iran in 2012 and her Ph.D. degree in Environmental Engineering from Babol Noshirvani University of Technology, Babol, Iran in 2020. She is currently a member of the Faculty of Civil Engineering at Tafresh University. Her research interests include Water and Wastewater treatment, Electrokinetic Soil Remediation, Electrocoagulation and Energy production by Microbial Fuel Cell.

Email: M.razavi@tafreshu.ac.ir
ORCID: 0000-0003-4229-3502

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