REVIEW ARTICLE

https://doi.org/10.21608/fpmpeb.2024.348450

Vol. 1, No 5/2024

A Review on Turning Waste into Wealth: Valorization Sewage Sludge as a Resource for Sustainable Energy

Mostafa Mohamed Basheir[1]*

[1] Former researcher in Chemistry and Microbiology Laboratory, Department of Environmental Science and Engineering, Marwadi University, Rajkot, Gujarat 360003, India

*Corresponding author: Mostafa Mohamed Basheir, mostafageo6@gmail.com

Abstract

The renewable energy sector is experiencing rapid growth as researchers, economists, and decision-makers aim to meet multiple objectives. These include generating energy from more sustainable and environmentally friendly sources, as well as addressing the increasing disparity between energy supply and demand in a market where demand continues to rise. It is important to seek a balance that ensures ongoing economic and industrial development while prioritizing environmental health. One promising solution in this regard is the production of biofuel from sewage sludge, which has a calorific value of 8,300 joules per gram. From an environmental perspective, achieving a reduction in greenhouse gas emissions necessitates a daily biofuel production target of 4.6×10^{7} gigajoules by 2040. This review will cover the knowledge about sewage sludge as a form of biomass and how to utilize raw materials in the production of various types of biomasses. Special focus will be given to selected biofuels, including biodiesel, bioethanol, and biogas, which serve as alternatives to their fossil fuel or natural gas counterparts.

Keywords: Fossil fuel; Sewage Sludge; Biodiesel; Bioethanol.

1. Introduction

Over the past few decades, the global energy demand increased due to industrial expansion and population growth. Contributing to this rise is the low cost associated with extracting fossil fuels, which has led to their dominance in the energy market. Fossil fuels currently hold the largest share, accounting for approximately 88% of the global energy market [1]. However, this dominance raises many significant economic and environmental concerns. Economically, fossil fuel reservoirs are finite and non-renewable, with extraction rates outpacing natural replenishment processes, which take millions of years [2]. Consequently, the depletion of fossil fuels, particularly oil, is inevitable, and the fate of newly discovered natural gas reserves may follow a similar trajectory. Reports suggested that fossil fuel reserves may be exhausted within the next 50 years, creating a substantial gap in future energy supply and posing serious repercussions for the global economy, which heavily relies on energy for its growth [3].

2. Exploring the Necessity for Non-Fossil Fuel Approaches to Energy Production

A study conducted in 2014 highlighted the decline of high-quality, easily accessible fossil fuel production. This decline is expected to result in an energy supply shortage across various sectors, including transportation, with projections suggesting an inability to meet electricity generation needs by 2025. However, some reports suggest that non-renewable resources, could help mitigate the anticipated supply-demand gap [4].

2.1 Environmental and Economic Concerns Associated with Fossil Fuel

The excessive consumption of energy, particularly from oil and natural gas, has led to the release of significant quantities of greenhouse gases (GHGs) into the atmosphere. These gases, including nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2), contribute to environmental degradation [5]. Among them, CO_2 is primarily responsible for global warming, posing a significant threat to the environment, although other GHGs are also concerning [6,7]. Annually, more than 15 billion tons of carbon dioxide are estimated to be released into the atmosphere [8]. Carbon dioxide emissions from fossil fuel combustion increased by 1.6% in 2017, This decline is expected to continue unless measures to reduce emissions are implemented [9].

The persistent environmental and economic concerns associated with fossil fuels have pointed out research into alternative and more sustainable sources of energy, with biomass emerging as one of the most promising options [7].

2.2 Biofuels: A Sustainable Energy Alternative

From an energy production perspective, biomass refers to organic materials rich in chemical energy derived primarily through photosynthesis in plants

[10]. Biomass offers the potential solution for reducing greenhouse gas emissions, aligning with efforts to limit global warming to no more than 2°C above pre-industrial levels, as outlined in the 2015 COP21 agreement in Paris [11].

Biofuels are categorized into four generations, each aiming to achieve sustainability by balancing economic growth with environmental protection and the conservation of natural resources. Biofuels are classified into four generations based on the feedstock used, the production processes involved, and the sustainability criteria they meet. Here's an overview of each generation:

1. First-generation biofuels: These biofuels are produced from edible crops or food-based feedstocks such as corn, sugarcane, soybeans, and palm oil. First-generation biofuels include biodiesel and bioethanol. While they have contributed to the development of the biofuel industry, first-generation biofuels have faced criticism for their competition with food crops, potential land use change, and limited sustainability. They also raise concerns about food security and deforestation.
2. Second-generation biofuels: Also known as advanced biofuels, second-generation biofuels are produced from non-edible feedstocks such as agricultural residues (corn stover, wheat straw), forestry residues, energy crops (miscanthus, switchgrass), and municipal solid waste. The production processes typically involve more advanced technologies such as biochemical and thermochemical conversion methods, including fermentation, gasification, and pyrolysis. Second-generation biofuels offer the potential to address some of the sustainability issues associated with first-generation biofuels by utilizing non-food feedstocks and reducing competition with food production.
3. Third-generation biofuels: These biofuels are derived from algae, microalgae, or other aquatic plants. Algae can be cultivated in various environments, including freshwater, saltwater, and wastewater, using a range of cultivation systems such as open ponds, photobioreactors, and closed-loop systems. Third-generation biofuels have the potential to offer high productivity and resource efficiency compared to terrestrial crops. Algae can accumulate high levels of lipids (oils) or carbohydrates, which can be converted into biofuels such as biodiesel or bioethanol through extraction and conversion processes.
4. Fourth-generation biofuels: This category encompasses biofuels produced from lignocellulosic biomass using advanced biotechnological approaches, such as synthetic biology and genetic engineering. Fourth-generation biofuels aim to maximize energy yields while minimizing environmental impacts and resource requirements. These biofuels utilize non-food lignocellulosic feedstocks, such as agricultural residues, dedicated energy crops, and woody biomass. Advanced conversion technologies, including enzymatic hydrolysis, fermentation, and bio-refining, are employed to extract sugars and convert them into biofuels such as bioethanol, biobutanol, or renewable diesel.

Each generation of biofuels represents advancements in technology and sustainability practices, with a focus on improving efficiency, reducing greenhouse gas emissions, and minimizing competition with food production.

These biofuels result from biochemical or chemical conversion processes, often involving fermentation with microorganisms as a key tool [12-14]. To meet the targets set by COP21 and effectively reduce greenhouse gas emissions to mitigate global warming, daily biofuel production must reach 4.6×10^7 gigajoules by 2040.

3. Sewage Sludge: A Potential Biofuel Resource

Sewage sludge (SS), also known as biosolids, is a byproduct of wastewater treatment processes and is considered one of the most pressing environmental challenges today [15,16]. SS represents a form of biomass with a high organic content, comprising 60-80% of the total SS material. The organic fraction includes 8-15% carbohydrates, 6-35% fats, 20-30% proteins, and microorganism cells, with a calorific value of approximately 8300 joules per gram of dry sewage sludge. Various biofuels can be derived from SS through conversion treatments such as thermal processes or chemical/biochemical reactions, including biochar, biodiesel, bioethanol, and biogas [17,18].

This review highlights the use of sewage sludge as a renewable resource for biofuel production, emphasizing its potential as a biomass source. It will also cover current research trends that consider sewage sludge not as an environmental burden but as a valuable raw material that can be effectively managed and utilized in various applications.

3.1 Examining the Need for New Water Sources and Water Treatment

Water is crucial for sustaining life as it plays a vital role in supporting biochemical reactions and physiological processes essential for human health and well-being. Comprising 80 to 90% of blood composition, water acts as a regulator of body temperature that facilitates the absorption of nutrients, vitamins, and minerals, while also enhancing blood circulation [19]. Despite covering about 70% of the Earth's surface, most of the stated water is saltwater, with only a small fraction being fresh water. Moreover, merely 0.3% of fresh water is readily accessible for human use [20]. As the global population continues to grow, the demand for fresh water intensifies, particularly for activities like agriculture and industrial processes, leading to increased pressure on fresh water resources. Consequently, the availability of safe drinking water has declined, resulting in water poverty affecting approximately 1.2 billion people [21].

3.2 Wastewater Treatment Practices in Egypt

To address these challenges, maximizing the utilization of available water sources becomes imperative. One approach to lessen pressure on fresh water resources involves the reuse of wastewater, wherein its quality is enhanced through improvements in its chemical, physical, and biological properties to suit various purposes [22]. Wastewater treatment serves as a crucial mean to achieve this objective by reducing pollutant levels and microbial loads in wastewater [23]. However, a byproduct of the wastewater treatment process is sewage sludge (SS), a semi-solid substance that harbors a significant proportion of pollutants and pathogens suspended in wastewater [24, 25].

Chemically, SS primarily comprises 70% organic matter, including proteins, fats, and carbohydrates, along with various inorganic compounds [26]. Despite expectations of a moderate increase in sewage sludge production, actual figures have surpassed estimates, with sewage sludge production reaching 45 million dry tons before 2020 in the European Union alone [27]. Similarly, in India, wastewater treatment capacities lag behind production rates, resulting in a significant portion of wastewater remaining untreated, exacerbating pollution concerns [28,29]. Additionally, the integration of industrial wastewater into sewage systems further compounds pollution issues, posing risks to human health and environmental integrity [30]. With only 60% of industrial wastewater being treated in India, the untreated portion remains contaminated, hindering widespread water reuse efforts [28].

In Egypt, the production of sewage sludge is on the rise due to same factors as those appointed in India. The rapid population growth, accompanied by the establishment of new cities to accommodate this expansion, elevates pollution levels. Addressing the population density issue requires the expansion of infrastructure, service facilities and industrial growth, all of which contribute to increased water consumption and, consequently, higher volumes of wastewater [31].

Over the past six decades (1950 – 2008), Egypt's population has escalated from 22 million to 80 million, resulting in an estimated annual increase of 1.5 million people [32]. The country is equipped with 303 wastewater treatment plants, producing an estimated 11.85×106 m^3/day of treated water, equivalent to 11850 MLD (Table 1). Comparing the annual wastewater production and treatment rates in both India and Egypt highlights the challenges faced by countries experiencing rapid industrialization and population growth. Recent statistics indicate that Egypt produces approximately 1.2 million tons of sewage sludge annually [33,34].

Table 1: Municipal wastewater production and treatment (Mato-Sagasta et al., 2015)

Country	**Municipal Wastewater (Km^3/year)**		
	Production	Treated	Year
Egypt	15.44	4.42	2011
India	7.08	3.71	2012

3.3 Water Treatment Strategies

As untreated wastewater continues to flow daily, there is an increase in demand to develop plans to manage these quantities effectively. This may involve increasing the capacity of existing treatment plants or establishing new ones. However, addressing sewage treatment poses another environmental challenge: the increase in sewage sludge production [29].

Sewage sludge contains a multitude of organic and inorganic pollutants and pathogens, which can pose significant environmental risks if released into the environment. Therefore, innovative strategies are required to manage sewage sludge effectively, with two primary objectives in mind:

1. Ensuring the safe disposal of sewage sludge.
2. Transforming sewage sludge from an environmental concern into a non-traditional resource that can be utilized in various aspects of life

These methods are widely regarded as effective means of sewage sludge disposal, offering significant economic and environmental advantages over traditional approaches [34]. This is particularly relevant given the growing global demand for non-renewable natural resources such as minerals and energy, as well as the increasing demand for food [35]. Governmental measures have been introduced to steer research efforts and investments toward the utilization of solid waste, including sewage sludge.

4. Transforming Sludge into Biofuel: Converting Waste into Wealth

Sewage sludge, a biosolid comprising organic materials, constitutes a significant portion of the sludge composition, primarily comprising human faeces, animal organic waste, food scraps, and other biodegradable materials found in sewage facilities [36]. Additionally, a diverse array of microorganisms involved in organic matter decomposition contributes to its composition. Considering this origin, sewage sludge emerges as a form of biomass that is proving valuable as a raw material for biofuel production [37]. The rationale behind utilizing sewage sludge lies in two fundamental factors. Firstly, there is a steady increase in annual sewage sludge production globally, driven by the expanding human population [38]. Secondly, sewage sludge predominantly consists of organic matter, comprising 60% of its dry material. However, it also contains contaminants such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and various heavy metals, posing environmental and health concerns [39]. While sewage sludge holds promise as a renewable resource in applications such as agriculture, its high pollutant content necessitates cautious handling to avoid adverse effects on agricultural ecosystems. Alternative methods of sewage sludge management, such as landfilling, may lead to terrestrial ecosystem pollution and potential greenhouse gas emissions [40].

Given its organic-rich composition, sewage sludge presents an ideal candidate for energy production. Utilizing sewage sludge management for energy generation offers a safe disposal method [41].

The direct combustion of biomass is often considered suboptimal for energy production due to its potential environmental impact and inefficiency in fully harnessing the energy stored in organic molecules [42]. To overcome these challenges associated with direct combustion, extensive research has been directed towards converting biomass, including sewage sludge, into various forms of biofuels that can exist in solid, liquid, and gaseous states [43].

Several technologies have been developed for biofuel production, categorized into two primary pathways: thermochemical and biochemical [44,45]. (Fig. 1) illustrates the biochemical and thermochemical pathways employed in converting biomass into biofuels. Thermochemical pathways involve the use of heat sources and controlled oxygen atmospheres to facilitate transformation processes, ensuring planned outcomes. In contrast, biochemical pathways rely on biological technologies, such as fermentation, where enzymes play a pivotal role in selectively processing carbohydrate materials within biomass to produce liquid and gaseous biofuels through microbial systems [46].

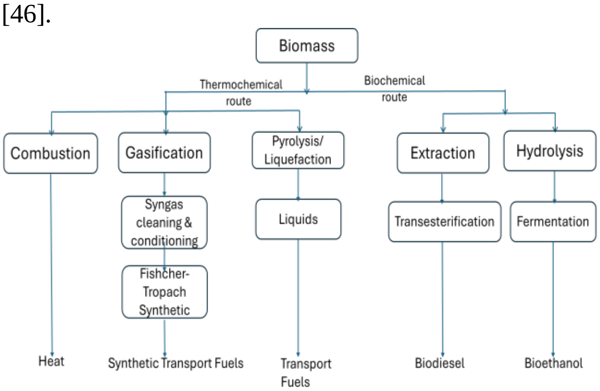

Figure 1. Thermochemical and biochemical pathways of biomass conversion to biofuels (Adapted: Sikarwar et al 2017).

Below is a simplified presentation of some examples of types of biofuel extracted from sewage sludge as an example of biomass:

4.1 Biodiesel Production from Sewage Sludge

Biodiesel serves as a renewable energy alternative to fossil-derived diesel oil, requiring no modifications for direct use in diesel engines [47]. It has advantages over petroleum diesel, including a higher flash point, lower viscosity, enhanced lubrication, and greater biodegradability [48]. Moreover, biodiesel significantly reduces carbon emissions and produces fewer air-polluting particulates, while its low toxicity ensures safer storage and handling, aligning with environmental regulations [49].

Chemically, biodiesel comprises alkyl esters of fatty acids, such as Fatty Acid Methyl Esters (FAMEs), produced through the transesterification reaction of fatty acids, triglycerides, or alcohol in the presence of base and/or acid catalysts [50]. However, conventional transesterification using homogeneous base catalysts like KOH or NaOH becomes inefficient due to the presence of large amounts of free fatty acids, leading to catalyst consumption and saponification issues [51]. As an alternative, strong acid catalysts have been employed to mitigate these challenges by reducing free fatty acid content and enhancing transesterification efficiency, enabling biodiesel production from low-quality feedstocks with high free fatty acid content [52].

4.2 Bioethanol Production from Sewage Sludge

Bioethanol, derived from biomass, represents another renewable energy source produced from both simple and complex sugars through various biochemical reactions facilitated by microorganisms [53,54]. Sewage sludge, containing lignocellulosic materials like cellulose, hemicellulose, and lignin, serves as a viable feedstock for bioethanol production through a sequence of physical and biochemical processes including hydrolysis, fermentation, and distillation [55,56].

Microorganisms, acting as biocatalysts, play a pivotal role in bioethanol production, enhancing reaction efficiency and minimizing waste in raw material utilization [57]. Various microorganisms such as *Saccharomyces cerevisiae*, *S. diastatitus*, *Kluyveromyces marxianus*, and others have been utilized for their ability to produce bioethanol effectively, with *Saccharomyces cerevisiae* being the most widely employed due to its efficiency [58].

Additionally, the use of wheat grains, a staple food source, has gained traction in ethanol production by converting starch into ethanol through fermentation, with approximately 374 liters of ethanol produced per ton of wheat grains [59,60]. This approach aims to minimize pressure on food sources for energy production, aligning with the principles of the circular economy.

Furthermore, sewage sludge from the edible oil industry presents an opportunity for renewable energy production. Instead of landfilling sewage sludge resulting from oil crop seed treatment, maximizing its utilization as a raw material in energy production is essential to mitigate environmental pollution [61].

Maximizing the utilization of oil wastewater sludge (OWS), bioethanol can be produced from oil extracted from OWS, obtained from the production and refining of edible oil, utilizing ethanol and n-hexane as solvents. This process yields residues after extraction (RAE), which serve as the substrate for bioethanol production through a series of treatments (hydrolysis, fermentation, and distillation), resulting in the efficient extraction of bioethanol [60]. This approach enables the production of two types of biofuels from a single raw material, enhancing resource efficiency and sustainability.

4.3 Biogas Production From Sewage Sludge

The production of gaseous fuels like hydrogen and methane from biomass stands as a crucial research focus in the realm of environmentally friendly renewable energy, with biogas production offering numerous advantages [62].

According to Chandra et al. (2012) [8], gaseous biofuels boast the following characteristics:

1. They are derived from renewable resources.
2. They emit significantly lower levels of greenhouse gases (GHGs) compared to natural gas.
3. Production occurs locally without dependence on external supplies, unlike natural gas.
4. They represent an effective method for managing solid waste of biological origin.

Annually, the global production of biomass reaches approximately 220 billion dry tons (Hall and Rosillo-Calle, 1998). A portion of this biomass contributes to energy production, with various forms of solid waste of biological origin, such as wood waste (64%), municipal solid waste (sewage sludge) (24%), agricultural waste (5%), and landfill gas (5%) [8].

Table 2: Comparison of gaseous emissions of selected fuels (modified from [8]).

Amount g/kg	**NO_x**	**HC**	**CO_2**	**CO**	**PM**
Diesel	9.73	0.40	1053	0.20	0.100
Natural gas	1.10	0.60	524	0.40	0.022
Biogas	5.44	0.35	223	0.08	0.015

Direct combustion of biomass leads to the emission of greenhouse gases, with approximately 1599 kg of CO2, 111.3 kg of CO, 92 kg of CH_4, 5.6 kg of HC, and 4.8 kg of PM emitted per ton of biomass [63]. Methane emissions resulting from the natural decomposition of biomass are a significant concern due to their potency as a greenhouse gas. The IPCC highlighted in 2001 that methane's global warming potential over a century is 23 times greater than that of CO_2 emissions (Table 2). Biogas emissions generally exhibit lower levels of gases responsible for global warming compared to other fuel sources, except for nitrogen oxides, where biogas emissions are approximately 4.9 times higher compared to natural gas emissions [64].

5. Conclusion

With the ever-increasing demand for energy and the finite nature of traditional energy resources, such as oil, there's a pressing need to explore alternative, environmentally friendly, and sustainable energy sources. This has led to a shift towards renewable energy production from sources like solar and wind power.

Biomass stands out as a promising candidate for energy production due to its versatility and renewability. Derived from organic materials, biomass can be utilized in solid, liquid, and gaseous forms, closely resembling natural gas, petroleum, and their derivatives in nature and consumption methods. Sewage sludge, a type of biomass, is particularly noteworthy for its high organic content, making it rich in energy potential.

Despite its energy potential, sewage sludge poses environmental and health risks due to the presence of organic and inorganic pollutants, as well as its role as a habitat for pathogens, insects, and harmful animals. Effective disposal of sewage sludge is imperative to minimize its adverse effects on health and the environment.

Biochemical and thermochemical conversion processes offer viable pathways for the safe disposal of sewage sludge while simultaneously maximizing its economic value. These processes can transform sewage sludge into alternative fuels, reducing reliance on finite fossil fuels and alleviating pressure on these non-renewable resources.

By shifting the perspective on sewage sludge from a nuisance to a valuable resource, we can explore its potential as a sustainable energy source. This involves rethinking traditional disposal methods like landfilling or agricultural use, which can lead to environmental pollution. Embracing sewage sludge as an unconventional energy resource holds the key to achieving sustainable energy production while addressing environmental concerns.

6. References

1. Li P, Sakuragi K, Makino H. Extraction techniques in sustainable biofuel production: A concise review. Fuel Processing Technology. 2019;193:295-303. https://doi.org/10.1016/j.fuproc.2019.05.009

2. Höök M, Bardi U, Feng L, Pang X. Development of oil formation theories and their importance for peak oil. Marine and Petroleum Geology. 2010;27(9):1995-2004.

https://doi.org/10.1016/j.marpetgeo.2010.06.005
3. Chew KW, Chia SR, Show PL, Yap YJ, Ling TC, Chang JS. Effects of water culture medium, cultivation systems and growth modes for microalgae cultivation: A review. Journal of the Taiwan Institute of Chemical Engineers. 2018;91:332-344. https://doi.org/10.1016/j.jtice.2018.05.039
4. Capellán-Pérez I, Mediavilla M, de Castro C, Carpintero Ó, Miguel LJ. Fossil fuel depletion and socio-economic scenarios: An integrated approach. Energy. 2014;77:641-666. https://doi.org/10.1016/j.energy.2014.09.063
5. Rutz D, Janssen R. Biofuel technology handbook. WIP Renewable energies. 2007;95.
6. Ahmed R, Huddersman K. Review of biodiesel production by the esterification of wastewater containing fats oils and grease (FOGs). Journal of Industrial and Engineering Chemistry. 2022;110:1-14. https://doi.org/10.1016/j.jiec.2022.02.045
7. Djandja OS, Wang ZC, Wang F, Xu YP, Duan PG. Pyrolysis of municipal sewage sludge for biofuel production: a review. Industrial & Engineering Chemistry Research. 2020;59(39):16939-16956. https://doi.org/10.1021/acs.iecr.0c01546
8. Chandra R, Takeuchi H, Hasegawa T. Methane production from lignocellulosic agricultural crop wastes: A review in context to second generation of biofuel production. Renewable and Sustainable Energy Reviews. 2012;16(3):1462-1476. https://doi.org/10.1016/j.rser.2011.11.035
9. Khoo KS, Chew KW, Yew GY, Leong WH, Chai YH, Show PL, Chen WH. Recent advances in downstream processing of microalgae lipid recovery for biofuel production. Bioresource Technology. 2020;304:122996. https://doi.org/10.1016/j.biortech.2020.122996
10. Petrus L, Noordermeer MA. Biomass to biofuels, a chemical perspective. Green chemistry. 2006;8(10):861-867. https://doi.org/10.1039/b605036k
11. Mulcahy DN, Mulcahy DL. How diplomacy saved the COP21 Paris Climate Conference, but now, can we save ourselves?. Frontiers in Energy. 2018;12:344-352. https://doi.org/10.1007/s11708-017-0498-y
12. Fulton LM, Lynd LR, Körner A, Greene N, Tonachel LR. The need for biofuels as part of a low carbon energy future. Biofuels, Bioproducts and Biorefining. 2015;9(5):476-483. https://doi.org/10.1002/bbb.1559
13. Alalwan HA, Alminshid AH, Aljaafari HA. Promising evolution of biofuel generations. Subject review. Renewable Energy Focus. 2019;28:127-139. https://doi.org/10.1016/j.ref.2018.12.006
14. Correa DF, Beyer HL, Fargione JE, Hill JD, Possingham HP, Thomas-Hall SR, Schenk PM. Towards the implementation of sustainable biofuel production systems. Renewable and Sustainable Energy Reviews. 2019;107:250-263. https://doi.org/10.1016/j.rser.2019.03.005
15. Wang J, Wang J. Application of radiation technology to sewage sludge processing: a review. Journal of Hazardous Materials. 2007;143(1-2):2-7. https://doi.org/10.1016/j.jhazmat.2007.01.027
16. Singh RP, Agrawal M. Potential benefits and risks of land application of sewage sludge. Waste management. 2008;28(2):347-358. https://doi.org/10.1016/j.wasman.2006.12.010
17. Bharathiraja B, Chakravarthy M, Kumar RR, Yuvaraj D, Jayamuthunagai J, Kumar RP, Palani S. Biodiesel production using chemical and biological methods-A review of process, catalyst, acyl acceptor, source and process variables. Renewable and Sustainable Energy Reviews. 2014;38:368-382. https://doi.org/10.1016/j.rser.2014.05.084
18. Rodríguez NH, Martínez-Ramírez S, Blanco-Varela MT, Donatello S, Guillem M, Puig J, Flores J. The effect of using thermally dried sewage sludge as an alternative fuel on Portland cement clinker production. Journal of Cleaner Production. 2013;52:94-102. https://doi.org/10.1016/j.jclepro.2013.02.026
19. Kılıç Z. The importance of water and conscious use of water. International Journal of Hydrology. 2020;4(5):239-241. https://doi.org/10.15406/ijh.2020.04.00250
20. Jain K, Patel AS, Pardhi VP, Flora SJS. Nanotechnology in wastewater management: a new paradigm towards wastewater treatment. Molecules. 2021;26(6):1797. https://doi.org/10.3390/molecules26061797
21. Tee PF, Abdullah MO, Tan IAW, Rashid NKA, Amin MAM, Nolasco-Hipolito C, Bujang K. Review on hybrid energy systems for wastewater treatment and bio-energy production. Renewable and Sustainable Energy Reviews. 2016;54:235-246. https://doi.org/10.1016/j.rser.2015.10.011
22. Chen H, Chen A, Xu L, Xie H, Qiao H, Lin Q, Cai K. A deep learning CNN architecture applied in smart near-infrared analysis of water pollution for agricultural irrigation resources. Agricultural Water Management. 2020;240:106303. https://doi.org/10.1016/j.agwat.2020.106303
23. Rorat A, Courtois P, Vandenbulcke F, Lemiere S. Sanitary and environmental aspects of sewage sludge management. In Industrial and Municipal Sludge (pp. 155-180). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-12-815907-1.00008-8
24. Burge WD, Cramer WN, Epstein E. Destruction of pathogens in sewage sludge by composting. Transactions of the ASAE. 1978;21(3):510-514. https://doi.org/10.13031/2013.35335
25. Pillai SD, Widmer KW, Dowd SE, Ricke SC. Occurrence of airborne bacteria and pathogen indicators during land application of sewage sludge. Applied and Environmental Microbiology. 1996;62(1):296-299. https://doi.org/10.1128/aem.62.1.296-299.1996
26. Templeton MR, Butler D. Introduction to wastewater treatment. Bookboon. 2011.
27. Zhang Q, Hu J, Lee DJ, Chang Y, Lee YJ. Sludge treatment: Current research trends. Bioresource Technology. 2017;243:1159-1172. https://doi.org/10.1016/j.biortech.2017.07.070
28. Kaur R, Wani SP, Singh AK, Lal K. Wastewater production, treatment and use in India. National Report presented at the 2nd regional workshop on Safe Use of

Wastewater in Agriculture. 2012 May:1-13.
29. Mateo-Sagasta J, Raschid-Sally L, Thebo A. Global wastewater and sludge production, treatment and use. Wastewater: Economic asset in an urbanizing world. 2015:15-38. https://doi.org/10.1007/978-94-017-9545-6_2
30. Saha O, Sultana A, Nikkon Sarker M, Siddiqui AR, Hossen F, Mukharjee SK. Biomass as a renewable resource for energy and chemical products. Sci. J. Energy Eng. 2017;5(6):146. https://doi.org/10.11648/j.sjee.20170506.13
31. Ayoub M, Rashed IGA, El-Morsy A. Energy production from sewage sludge in a proposed wastewater treatment plant. Civil Engineering Journal. 2016 Dec;2(12):637-45. https://doi.org/10.28991/cej-2016-00000064
32. Khalifa M, DaVanzo J, Adamson DM. Population growth in Egypt: A continuing policy challenge. Rand. 2000. https://doi.org/10.7249/IP183
33. Ghazy M, Dockhorn T, Dichtl N. Sewage sludge management in Egypt: Current status and perspectives towards a sustainable agricultural use. International Journal of Environmental and Ecological Engineering. 2009 Sep;3(9):270-8.
34. Wahaab RA, Mahmoud M, van Lier JB. Toward achieving sustainable management of municipal wastewater sludge in Egypt: the current status and future prospective. Renewable and Sustainable Energy Reviews. 2020 Dec 1;127:109880. https://doi.org/10.1016/j.rser.2020.109880
35. Pappu A, Saxena M, Asolekar SR. Solid wastes generation in India and their recycling potential in building materials. Building and environment. 2007 Jun 1;42(6):2311-20. https://doi.org/10.1016/j.buildenv.2006.04.015
36. Trabelsi ABH, Zaafouri K, Friaa A, Abidi S, Naoui S, Jamaaoui F. Municipal sewage sludge energetic conversion as a tool for environmental sustainability: production of innovative biofuels and biochar. Environ Sci Pollut Res. 2021 Feb;28(8):9777-91. https://doi.org/10.1007/s11356-020-11400-z
37. Saha S, Saha BN, Pati S, Pal B, Hazra GC. Agricultural use of sewage sludge in India: benefits and potential risk of heavy metals contamination and possible remediation options-a review. International Journal of Environmental Technology and Management. 2017 Dec 1;20(3-4):183-99. https://doi.org/10.1504/IJETM.2017.089645
38. Di Giacomo G, Romano P. Evolution and Prospects in Managing Sewage Sludge Resulting from Municipal Wastewater Purification. Energies. 2022 Nov 30;15(23):5633. https://doi.org/10.3390/en15155633
39. Fijalkowski K, Rorat A, Grobelak A, Kacprzak MJ. The presence of contaminations in sewage sludge-The current situation. Journal of environmental management. 2017 Dec 1;203:1126-36. https://doi.org/10.1016/j.jenvman.2017.05.068
40. Marin E, Rusănescu CO. Agricultural use of urban sewage sludge from the Wastewater Station in the municipality of Alexandria in Romania. Water. 2023 Jan 23;15(3):458. https://doi.org/10.3390/w15030458
41. Sugurbekova G, Nagyzbekkyzy E, Sarsenova A, Danlybayeva G, Anuarbekova S, Kudaibergenova R, Frochot C, Acherar S, Zhatkanbayev Y, Moldagulova N. Sewage sludge management and application in the form of sustainable fertilizer. Sustainability. 2023 Apr 1;15(7):6112. https://doi.org/10.3390/su15076112
42. Kar T, Keles S. Environmental impacts of biomass combustion for heating and electricity generation. Journal of Engineering Research and Applied Science. 2016 Dec 30;5(2):458-65.
43. Osman AI, Mehta N, Elgarahy AM, Al-Hinai A, Al-Muhtaseb AA, Rooney DW. Conversion of biomass to biofuels and life cycle assessment: a review. Environmental chemistry letters. 2021 Dec;19:4075-118. https://doi.org/10.1007/s10311-021-01273-0
44. Abou Rjeily M, Gennequin C, Pron H, Abi-Aad E, Randrianalisoa JH. Pyrolysis-catalytic upgrading of bio-oil and pyrolysis-catalytic steam reforming of biogas: a review. Environmental Chemistry Letters. 2021 Aug;19(4):2825-72. https://doi.org/10.1007/s10311-021-01190-2
45. Peng L, Fu D, Chu H, Wang Z, Qi H. Biofuel production from microalgae: a review. Environmental Chemistry Letters. 2020 Mar;18:285-97. https://doi.org/10.1007/s10311-019-00939-0
46. Nanda S, Pattnaik F, Patra BR, Kang K, Dalai AK. A review of liquid and gaseous biofuels from advanced microbial fermentation processes. Fermentation. 2023 Sep 6;9(9):813. https://doi.org/10.3390/fermentation9090813
47. Tarigan JB, Ginting M, Mubarokah SN, Sebayang F, Karo-Karo J, Nguyen TT, et al. Direct biodiesel production from wet spent coffee grounds. RSC advances. 2019;9(60):35109-16. https://doi.org/10.1039/C9RA08038D
48. Centi G, Perathoner S. Catalysis by layered materials: A review. Microporous and mesoporous materials. 2008;107(1-2):3-15. https://doi.org/10.1016/j.micromeso.2007.03.011
49. Bharathiraja B, Yogendran D, Ranjith Kumar R, Chakravarthy M, Palani S. Biofuels from sewage sludge-A review. International Journal of ChemTech Research. 2014;6(9):4417-27.
50. Qi J, Zhu F, Wei X, Zhao L, Xiong Y, Wu X, et al. Comparison of biodiesel production from sewage sludge obtained from the A2/O and MBR processes by in situ transesterification. Waste management. 2016;49:212-20. https://doi.org/10.1016/j.wasman.2016.01.029
51. McNeff CV, McNeff LC, Yan B, Nowlan DT, Rasmussen M, Gyberg AE, et al. A continuous catalytic system for biodiesel production. Applied Catalysis A: General. 2008;343(1-2):39-48. https://doi.org/10.1016/j.apcata.2008.03.019
52. Ganesan S, Nadarajah S, Chee XY, Khairuddean M, Teh GB. Esterification of free fatty acids using ammonium ferric sulphate-calcium silicate as a heterogeneous catalyst. Renewable Energy. 2020;153:1406-17. https://doi.org/10.1016/j.renene.2020.02.094
53. Mtui GY. Recent advances in pretreatment of lignocellulosic wastes and production of value-added products. African Journal of Biotechnology.

2009;8(8).

54. Hsu CL, Chang KS, Lai MZ, Chang TC, Chang YH, Jang HD. Pretreatment and hydrolysis of cellulosic agricultural wastes with a cellulase-producing Streptomyces for bioethanol production. Biomass and Bioenergy. 2011;35(5):1878-84. https://doi.org/10.1016/j.biombioe.2011.01.031

55. Knauf M, Moniruzzaman M. Lignocellulosic biomass processing: a perspective. International sugar journal. 2004;106(1263):147-50.

56. Limayem A, Ricke SC. Lignocellulosic biomass for bioethanol production: current perspectives, potential issues and future prospects. Progress in energy and combustion science. 2012;38(4):449-67. https://doi.org/10.1016/j.pecs.2012.03.002

57. Mbohwa C, Manyuchi MM, Muzenda E, Mutusva T, Chiutsi P. Bioethanol from sewage sludge: A biofuel alternative. South African journal of chemical engineering. 2018;25(1):123-7. https://doi.org/10.1016/j.sajce.2018.04.003

58. Taouda H, Chabir R, Aarab L, Miyah Y, Errachich F. Biomass and bioethanol production from date extract. J Mater Environ Sci. 2017;8(9):3391-6.

59. Murphy JD, Power NM. How can we improve the energy balance of ethanol production from wheat?. Fuel. 2008;87(10-11):1799-806. https://doi.org/10.1016/j.fuel.2007.12.011

60. Ngoie WI, Oyekola OO, Ikhu-Omoregbe D, Welz PJ. Valorisation of edible oil wastewater sludge: bioethanol and biodiesel production. Waste and biomass valorization. 2020;11:2431-40. https://doi.org/10.1007/s12649-019-00633-w

61. Kumar D, Singh V. Dry-grind processing using amylase corn and superior yeast to reduce the exogenous enzyme requirements in bioethanol production. Biotechnology for biofuels. 2016;9(1):1-12. https://doi.org/10.1186/s13068-016-0648-1

62. Simpson-Holley M, Higson A, Evans G. Bring on the biorefinery. Chemical engineer. 2007(795):46-8.

63. Neto TS, Carvalho Jr JA, Veras CAG, Alvarado EC, Gielow R, Lincoln EN, et al. Biomass consumption and CO2, CO and main hydrocarbon gas emissions in an Amazonian forest clearing fire. Atmospheric Environment. 2009;43(2):438-46. https://doi.org/10.1016/j.atmosenv.2008.07.063

64. Rutz D, Janssen R. Biofuel technology handbook. WIP Renewable energies. 2007.

Timeline of Publication

Received	**Date:**	29	January	2024
Revised	**Date:**	7	February	2024
Accepted	**Date:**	26	February	2024
Published	**Date:**	1	Mach	2024