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Review

Renewable Energy Products through Bioremediation of Wastewater

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Abstract: Due to rapid urbanization and industrialization, the population density of the world is intense in developing countries. This overgrowing population has resulted in the production of huge amounts of waste/refused water due to various anthropogenic activities. Household, municipal corporations (MC), urban local bodies (ULBs), and industries produce a huge amount of waste water, which is discharged into nearby water bodies and streams/rivers without proper treatment, resulting in water pollution. This mismanaged treatment of wastewater leads to various challenges like loss of energy to treat the wastewater and scarcity of fresh water, beside various water born infections. However, all these major issues can provide solutions to each other. Most of the wastewater generated by ULBs and industries is rich in various biopolymers like starch, lactose, glucose lignocellulose, protein, lipids, fats, and minerals, etc. These biopolymers can be converted into sustainable biofuels, i.e., ethanol, butanol, biodiesel, biogas, hydrogen, methane, biohythane, etc., through its bioremediation followed by dark fermentation (DF) and anaerobic digestion (AD). The key challenge is to plan strategies in such a way that they not only help in the treatment of wastewater, but also produce some valuable energy driven products from it. This review will deal with various strategies being used in the treatment of wastewater as well as for production of some valuable energy products from it to tackle the upcoming future demands and challenges of fresh water and energy crisis, along with sustainable development.

Keywords: effluent; anaerobic digestion; incineration; Co-pyrolysis; syngas; biodiesel; biofuel

1. Introduction

All living beings could not live without water. Humans require water for not only to sustain their life, but also to accomplish their day to day activities. But now, a day's pure water gets out of reach of humans because of the addition of various harmful and toxic pollutants in water sources. Beside this basic necessity of the present world, the management of resulting effluent or wastewater is another challenge [1,2]. While technologies for the recovery of wastewater resources have been discussed extensively by the scientific community in recent decades, their large-scale implementation in municipal wastewater treatment facilities (WWTPs) still requires serious consideration. This can be demonstrated mainly by technical and non-technical reasons for doing so. Wastewater management plays a significant part in sustainable urban planning [3]. It is a well-known worldwide reality that the energy demand is increasingly growing due to rapid population growth that has also increased the rate of generation of wastewater in the last decades. To accomplish both of these obligations, utilization of wastewater should be done in such a manner so that the process used would treat the wastewater along with the production of some cherished products which can be reutilized further [4,5]. Use of waste water for energy generation is economic, as this does not require expensive phenomenon. While several emerging technologies contribute to the wastewater resource recovery challenge, biological approaches give the greatest promise to recover essential resources from effluent in an efficient manner. The article will generally concentrate on various methods of resource recovery from domestic and industrial wastewater [6]. The next generation of Domestic Wastewater Treatment Plants (DWWTP) targets energy efficiency and the complete use of wastewater for energy generation. There are also increasing concerns to extract useful products, especially renewable energy, from various forms of waste and wastewater from various industrial effluents [7]. Moreover, the fossil sources are very limited and may deplete in the coming future, so alternative sources of energy have to be developed. Therefore, the best approaches include the use of wastewater for production of energy products like bioethanol, biogas, biodiesel, etc., which further can be transformed into electricity [8]. Such energy recovery approaches may help mitigate wastewater sector electricity consumption and show promising areas for renewable energy policy implementation. Our analysis looks only at energy usage and future savings; while very significant, the economics of energy recovery mechanisms of wastewater treatment plants are reserved for a separate examination.

2. Characteristics of Wastewater

The characteristics of wastewater significantly affect the treatment approach to be pursued, as well as the reactor design selection process. For such characteristics, the most important are concentration for suspended solids, organic strength (BOD or COD), temperature, pH, and inhibitor presence [9]. Many reactor designs can damaged by suspended solids and accumulation of grits. For this purposes, liquid waste or wastewater is considered to have a concentration of suspended solids below 1000 mg/L with small quantities of grit (inorganic non-soluble solids), often removed by simple pretreatment. Defined as such, wastewater can be graded as low, i.e., below 1000 for industrial, agricultural (including flushed manures), and pulp and paper, medium, i.e., 1000–10,000 for food processing, canning, citrus processing, milk processing, juice processing, and brewery, and high, i.e., 10,000–200,000 for ethanol production, distillery, biodiesel production, petrochemical, and slaughter house concentration [10–12].

2.1. Sources of Wastewater

On the basis of the source from which the wastewater is being generated, there are various types of wastewater, some of them are listed below:

1. Domestic Wastewater (DW)
2. Sewage Sludge (SS)
3. Diary Wastewater (DWW)
4. Winery Wastewater (WWW)
5. Tannery Wastewater (TWW)
6. Textile Wastewater (TxWW)
7. Food Wastewater (FWW)
8. Phenolic Wastewater (PWW)
9. Carpet Mill Wastewater (CMWW)
10. Slaughter House Wastewater (SHWW)
11. Pharmaceuticals Wastewater (PhWW)
12. Beverage Wastewater (BWW)
13. Paper industry Wastewater (PWW)
14. Palm Oil Mill Wastewater (POMW)
15. Olive Oil Mill Wastewater (OOMW)

2.2. Features and Pollutnats of the Wastewater

Wastewater is generally characterized on the basis of physical (color, odor, and turbidity) and chemical (pH, alkalinity, biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), total organic carbon (TOC), total dissolved solids (TDS), total suspended solids (TSS), conductivity, nitrogen, phosphorus, heavy metals, volatile solids (VS), oil, fats, grease and gases), etc. Different types of sources, along with their typical properties, are listed and discussed in Table 1.

Table 1. Characteristics and sources of some wastewater effluents.

Waste Water Type	Sources	pH	Chemical Oxygen Demand (COD) (mg/L)	Biochemical Oxygen Demand (BOD) * (mg/L)	Dissolved Oxygen (DO) (mg/L)	Total Solids (g/L)	Total Dissolved Solids (TDS) (g/L)	Total Suspended Solids (TSS) (g/L)	(VS) (g/L)	Alkalinity (mg/L)	References
DW	Toilets	-	740	350	-	-	-	450	320	1850	[13]
DWW	Dairy or Milk Industry	3.3	4705	1800	6.3	43.62	5.3	38.32	39.84	-	[14]
FWW	Petha Sweet Industry	11.9	5882	580	3.8	5.44	5.22	0.22	1.64	2400	[15]
OOMW	Olive Mills	4.8	132,300	-	-	41.8	-	-	36.8	-	[16]
POMWW	Palm Oil Mills	4.2	51,000	25,000	-	-	-	18,000	-	-	[17]
SHWW	Slaughter House	5.3–6.8	58,000–20,150	2200–9800	-	-	-	2.4–4.7	-	-	[18]

* BOD after 5 days.

Most of the wastewater contains a chemical, biological matter, and other objectionable matter that differ from source to source from which it generates. Industrial effluent includes a significant quantity of harmful chemicals and heavy metals, i.e., zinc, copper, nickel, lead, cadmium, arsenic, antimony, mercury, etc. [19], with lower biological content. Wastewater from households contains lower levels of chemicals comparatively to industrial wastewater, but high levels of organic matter, whereas agricultural wastewater includes high levels of chemicals in the form of pesticides, weedicides, fertilizers, etc., and biological substances like algae, fungi, bacteria, etc. [5,20]. Waste water consists of 70% organic compounds and 30% inorganic compounds, along with a variety of gases. Organic compounds are mainly carbohydrates, fats, and proteins, whereas inorganic matter consists of heavy metals, nitrogen, phosphorus, sulphur, and chloride, etc. Hydrogen sulfide, methane, ammonia, oxygen, nitrogen, and carbon-dioxide are commonly dissolved gases present in wastewater [21]. Biologically, wastewater consists of different types liverworts, seedy plants, ferns and mosses, bacteria, fungi, algae, and protozoans along with various types pathogens are also found in wastewater, which comes from the human beings suffering from various diseases [20,22].

3. Treatment Methods of Wastewater

Various types of pollutants present in the wastewater can be removed by using different strategies. Various treatment methods are used on the basis of source and location for wastewater treatment. Primary treatment can reduce BOD by 20–30% and suspended solids by as much as 60% [23]. This step includes reduction of oil, grease, fats, sand, and coarse solids. Secondary treatment will minimize BOD and total suspended solids by up to 85 percent. This step includes degradation of dissolved contents of the sewage within a biological degradation of system, as shown in Figure 1. The last step of secondary treatment is the removal of biological matter from the treated water with very low levels of organic material and suspended solids [24]. Microbes in the wastewater consume food in the form of organic matter, turning it into carbon dioxide, water, and electricity. Tertiary treatment can remove up to 99 percent of sewage impurities. Some operators add chlorine as a disinfectant before discharging the water. Sometimes nitrogen and phosphorus removal are done by tertiary treatment. Tertiary treatment uses advanced equipment and technologies to further eliminate or discard contaminants or particular pollutants [25].

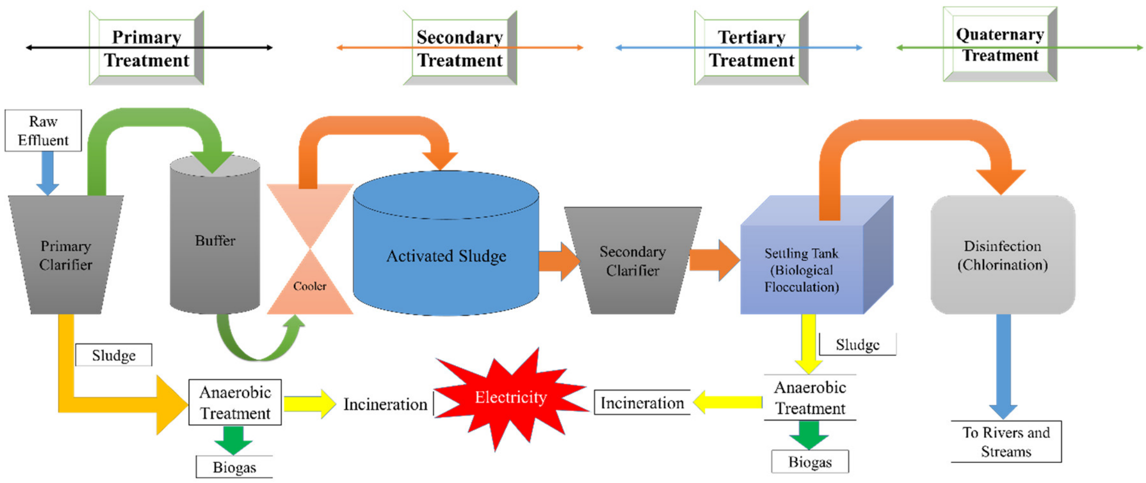

Figure 1. Schematic representation of waste treatment plant.

On the basis of type of matter present, ultrafiltration, sedimentation, sand filtration, etc., are physical methods used to treat the wastewater or industrial effluent as shown in Figure 2. In the chemical treatment method, chlorine is the most widely used chemical that acts as oxidizing agent to kill the bacteria that decompose the water. Another disinfecting oxidizing agent called ozone is used to purify wastewater [10]. Biological treatment methods use biological agents like plants and microorganisms in this way to remove the harmful pollutants. Biological wastewater treatment is done by oxidation bed or aerated systems, and post precipitation. It can be classified into various groups such as aerobic, anaerobic, and anoxic systems or suspended growth and attached growth according to the growth mechanism of microorganisms [26,27].

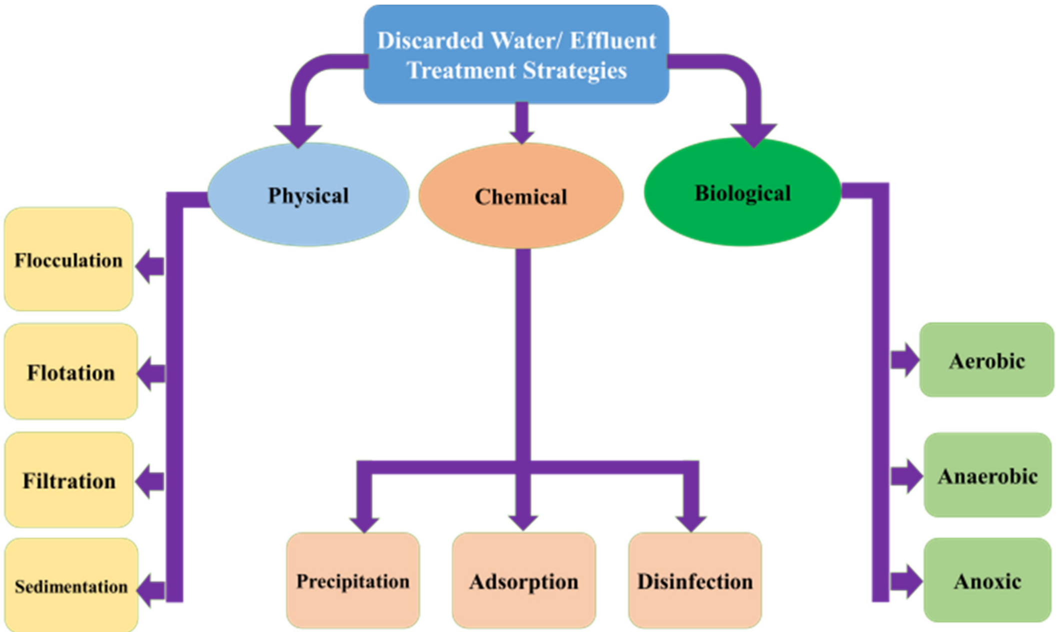

Figure 2. Different methods of wastewater treatment.

4. Wastewater as a Source of Renewable Energy

Wastewater produced by various sources is usually full of various minerals, nutrients, and organic matter, and these act as a wonderful source of metabolites for the growth and development of various microorganisms, algae, and plants which can be utilize to produce various renewable energy products. Organic matter rich wastewater, when decomposed in an oxygen-free environment, especially deep in a landfill, releases methane gas. Wastewater which is rich in organic matter when it decomposes, particularly deep in a landfill in an oxygen-free environment, releases methane gas [28]. This methane can be collected and used, instead of released into the atmosphere, to generate heat and electricity. Most wastewater treatment systems include different stages and eventually create solid sludge that is treated by thermal hydrolysis to increase the amount of methane it can generate. The processed waste then enters in an anaerobic digester, which ends up breaking it down. The resulting product is a methane-rich gas, or biogas, which can be used for on-site energy needs, or further refined and used instead of natural gas [29]. However, the solid wastewater residues produce a nutrient-rich "digestate" that can be used as a biofertilizer for soil conditioning and to improve plant production. Usually, the concentration of reducing matter in wastewater is expressed as the COD, which indicates how much oxygen is needed to oxidize the reducing matter [30]. A typical wastewater has a 0.5 kg/m^3 COD value and theoretically has the ability to generate 1.47 to 10^7 joules of energy per kg COD oxidized to CO_2 and H_2O, and the wastewater energy density is 0.74 to 10^7 J/m^3. Heidrich et al. [31] have recently statistically calculated the internal chemical energy of wastewater measured at 1.68×10^7 J/m^3 for wastewater combined with household wastewater and industrial wastewater, and 0.76×10^7 J/m^3 for pure household wastewater. Accordingly, a fair estimation of the theoretical energy density in wastewater is in the order of 10^7 J/m^3, which is five times the energy used to treat wastewater, and based on this data, the USA has an approximate capacity of 1.2×10^{15} J/day, 4.4×10^{17} J/year of wastewater renewable energy production [32–34].

4.1. Approaches to Determining Energy Potential from Wastewater

Process streams must be differentiated according to their capacity as energy sources according to the following input streams, process intermediates, and energy outputs in order to relate different technical options for energy recovery from wastewater.

4.1.1. Inputs

Carbonaceous material, especially the organic material (dissolved/suspended) present in wastewater, conducts its chemical energy potential. Exceptions are energy in the form of heat (for wastewater above ambient temperature) and the use of wastewater as growth media for species to absorb carbon dioxide using sunlight energy (photosynthesis) because of their inorganic constituents [35].

4.1.2. Intermediates

A number of intermediate compounds synthesized by the microorganisms, algae, and green plants that act as store houses of biochemical energy. These intermediary compounds are utilized by the microorganism as well animals to produce the energy to fulfill their energy requirement for day to day activities. But using some specific microorganisms, as well as advanced technological strategies, these compounds can also be utilize for the production of a number of energy products such as gaseous hydrogen or methane, liquid ethanol or biodiesel, or solid dry biomass [36].

4.1.3. Outputs

In particular, intermediate fuels provided by methane from wastewater can be used as energy products for heat, electricity generation, and even in propulsion vehicles. Currently available systems are much less effective and can transform only 25 to 35 percent of thermal energy into electrical energy, resulting in tremendous energy losses [8,37]. For higher recovery and better efficiencies, therefore, combined heat and power application is recommended. Therefore, technologies that convert inputs into intermediates by harnessing carbon-bound energy into biogas, bio-ethanol, and biodiesel, and then converting these intermediates into outputs via combustion/gasification into gaseous fuels, or converting inputs directly into outputs via heat recovery through heat pumps, and microbial fuel cells for electricity generation [38–40]. To maximize the potential for wastewater energy recovery, each of these technologies must first be understood in terms of physical, chemical, and biological concepts and constraints, and in terms of maturity and current penetration level.

4.2. Valuable Energy Products from Wastewater

Controlled treatment of wastewater can produce a variety of value-added items. Biological wastewater systems are commonly used to obtain valuable materials from wastewater. There may be either aerobic and anaerobic digestion, or effluent co-digestion. Wastewater treatment produces a large number of energy products that can be used in the form of biofuels, which are described in Table 2 as well as in the section below:

Table 2. Types of useful energy products recovered from different types of wastewater, and their characteristics and operational features.

Bioenergy Produced	Wastewater Stream (WWS)	Characteristic of WWS	Operating Conditions	Remarks	Reference
Biogas: Microorganisms involved- Acetogens and Methanogens.	Palm Oil Mill Effluent	High BOD and COD due to high organic content; pH = 3.4–5.2	Anerobic Digestion (AD) using Up-flow anaerobic sludge fixed film	71.9% CH_4	[41]
	Distillery Stillage	High COD and BOD due to presence of many organic compounds like polysaccharides, proteins, etc.	AD using Up-flow Anerobic Sludge Blanket (UASB)	90% COD; Biogas productivity = 0.43 m^3/kg.	[42]
	Textile printing and dyeing wastewater	High pH, high turbidity, poor biodegradability	AD using Anerobic Baffled Reactor; pH = 6.8–7.3; 30–35 °C; HRT = 4 days	83% CH_4; 71.5% COD removal	[43]
	Recycled Papermill Wastewater	Organic wastewater with high COD concentration	AD using UASB; 37 °C; OLR = 8.3 g COD/L/d; HRT = 15.14 h. d.	The highest biogas volume of 176.1 L/kg COD removed	[11]
	Cattle Slaughterhouse Wastewater	Rich in organic components and nutrient	AD using modified UASB; OLR of 10 g $L^{-1}d^{-1}$; HRT = 1 day	>90% COD removal; biogas (27 L/d); 89% CH_4	[44]
	Municipal Wastewater	High COD and BOD	AD using UASB and Dynamic Membrane Filter	Methane yield was 354 ± 37 mL CH_4/$gCOD_{utilized}$	[45]
	Molasses Wastewater	High amount of carbohydrates	AD using UASB	91.2% COD removal; 67.3%–78.9% CH_4	[46]
Bioethanol	Cassava Liquid Waste	Rich in glucose and starch	Acid/Enzyme pretreatment followed by SSF by *Zymomonas mobilis*	95% theoretical ethanol yield	[7]
	Municipal wastewater/Municipal Sewage sludge	Rich in organics	Saccharification by *Bacillus flexus* followed by fermentation by yeast 6% wt.; pH = 6.5; 30 °C; 10 days	Bioethanol yield are greater than 40 mL/L	[47]
	Agricultural Wastewater	Rich in organic nutrients	Algae cultivation followed by saccharification and fermentation	-	[39]
	Winery Wastewater	High concentration of organic and inorganic contaminants	Biorefinery concept	-	[48]
	Diary Wastewater	High COD and BOD due to presence of whey in liquid waste	Engineered *Lactobacillus lactis* can serve as novel cell factory; Fed Batch Strategy	71% Theoretical ethanol yield	[49]
	Olive mill wastewater	Rich in phenols and polyphenols	Biotreatment using: *Candida tropicalis*, *Pichia kudriavzevii*, *Pichia manshurica*, *Kluyveromyces marxianus*	Considerable amount of ethanol formed	[38]

Table 2. *Cont.*

Bioenergy Produced	Wastewater Stream (WWS)	Characteristic of WWS	Operating Conditions	Remarks	Reference
Biodiesel	Textile Wastewater	Contain variety of dyes, phosphates, nitrates, and auxiliary chemicals; high BOD, COD	Microalgal (*Chlorella* sp., *Scenedesmus* sp.) Bioremediation followed by harvesting, lipid extraction, and biodiesel production	Good yield of biodiesel obtained at lab scale with 60%–80% COD removal	[40]
	Diary Wastewater Sludge	Sludge contain 3–4% wt. total solids	Sludge dewatering and drying-two stage solvent extraction-Dewaxing-Drying-Transesterification-Washing	At optimum condition, 97.4% biodiesel yield from refined lipid	[50]
	Sago Processing Wastewater from Cassava based Industry	Rich in starch; high COD and BOD	Lipid production for biodiesel feedstock using *Candida tropicalis* ASY2	Innovative and ecologically sustainable technology with 84% COD removal, 92% BOD removal; high oleic acid content = 41.33%	[51]
	Tannery Wastewater	High oxygen demand	Microalgae Cultivation by *Chlorella* sp., *Scenedesmus* sp. Supplemented with Kelp waste extract	Good alternative for TWW treatment and biodiesel production	[52]
	Domestic Wastewater	Nutrient rich	Microalgae cultivation by *Nostoc* sp., *Chlorella* sp.	It is a suitable and non-expensive method for biodiesel production	[13]
Biohydrogen	Paper board Mill Wastewater	High organic and inorganic contaminants are present	Anerobic digestion by mixed culture bacteria (Hydrogen producer) using Continuous up flow anerobic reactor; HRT = 9.6 h	H_2 yield = 5.29 mmol/g COD (70%)	[53]
	Beverage Industry Wastewater (Alcohol distillery)	Rich in starch and glucose	Reactor- Anerobic Sequencing Batch Reactor; Inoculum- Sludge from Red Bull Distillery anerobic tank; HRT = 16 h	H_2 yield = 172 mL/g COD removed (34.7%)	[9]
	Sugary Wastewater	Rich in simple sugars	Reactor- Continuous Stirred Tank Reactor (CSTR); Inoculum- Municipal sewage treatment sludge; HRT = 1 h	H_2 yield = 1.37 mol/mol hexose (40%)	[54]
	Cheese Processing Wastewater	High COD and BOD due to whey	Reactor-CSTR; Inoculum-Anerobic digestor sludge; HRT = 24–84 h	H_2 yield = 5–22 mmol/g COD (45%)	[55]
	Rice mill wastewater	Rich in polysaccharides	After proper pretreatment and hydrolysis (Acid pretreatment with enzymatic hydrolysis); hydrogen produced using *Enterobacter aerogenes* RM 08 in Batch Reactor	H_2 yield = 1.97 mol H_2/mol sugar	[56]

Table 2. *Cont.*

Bioenergy Produced	Wastewater Stream (WWS)	Characteristic of WWS	Operating Conditions	Remarks	Reference
Bioelectricity	Kitchen Wastewater	High Organic and Protein content	Using Microbial Fuel Cell consisting photosynthetic microorganism as cathode catalyst (*Synecochococcus* sp. and *Chlorococcum* sp.); Anode Mixed culture; 1600 lx; CO_2 Supply	Power density = 41.48 mW/m^2 *Synecochococcus* sp.; 30.20 mW/m^2 *Chlorococcum* sp.	[37]
	Diary Wastewater	High COD and BOD	Dual chambered Microbial Fuel Cell is used with anolyte pH = 7	Aerobic metabolism gives Power density of 192 mW/m^2 with 91% COD removal while anerobic metabolism gives power density of 161 mW/m^2 with 90% COD removal	[12]
	Food processing wastewater	Rich polysaccharides, proteins; High BOD	Anode-Buffer solution; Cathode-Food processing wastewater; both are separated by proton exchange membrane in two compartment Microbial Fuel Cell (MFC) reactors; no catalyst and mediator	Power density = 230 mW/m^2 86% COD removal	[57]
	Sewage Sludge	Rich in organics	Anode-Graphite with neutral red (NR)/graphite with Mn^{4+}/platinum and polyanilineco-modified; Bacteria: *Escherichia coli; System configuration: Single Chamber*	Power density = 152/91/6000 mW/m^2 respectively	[58]
Microbial Fuel Cell	Swine Wastewater	8320 mg/L soluble COD	Single chambered MFC; Carbon paper electrode; cathode covered with platinum one side	261 mW/m^2	[59]
	Urban Wastewater	Low BOD	Salt bridge is present; graphite electrodes	25 mW/m^2	[60]
	Beer brewery Wastewater	2240 mg/L COD	Single Chamber, air cathode MFC, carbon cloth electrodes	205 mW/m^2	[61]
	Wastewater from Paper recycling industry	High organic and inorganic contaminants are present	Mixed culture of *Enterobacter* sp., U-tube MFC	5.5 mW/m^2	[62]
	Chocolate Industry Wastewater	1459 mg/L COD	Activated sludge from Municipal Wastewater treatment plant; dual chambered MFC; Graphite electrodes	1500 mW/m^2	[63]
	Starch Processing Wastewater	Rich in glucose and starches	Air cathode MFC; carbon paper anode	239.4 mW/m^2	[64,65]
	Sewage Sludge	12,110 mg/L Total COD	Two chambered MFC; graphite fiber brush electrodes	9.1 W/m^3	[66,67]

4.2.1. Biogas

Biogas is produced in an oxygen-free environment by anaerobic digestion of organic matter using microorganisms. Biogas processing requires several stages of a number of microorganisms: Microorganisms turn complex organic compounds into less complex organic compounds that are then converted into organic acids in initial hydrolysis reactions. Then methane forming microorganisms use these acids to form methane, the principal component of biogas [2,11]. Biogas is a mixture of gases containing typically 50–70% of methane. In addition, anaerobic digestion can produce hydrogen either as a component of the biogas, or as the major product. The latter requires that particular species, such as *Rhodobacter* or *Enterobacter* sp., to dominate the microbial population [41,44]. Current models indicate significantly greater recovery of energy from the digestion of biomass as methane. Hydrogen fermentation may become more attractive with the advancement of fuel-cell technology. Biogas can be used with little alteration in many applications (Stoves, Boilers). The gas needs substantial modifications for applications in combustion engines (generators, motor car engines) in order to eliminate non-methane components [2,29].

4.2.2. Bioethanol

Generally, bioethanol is produced from lignocellulosic biomass, but due to advancements in wastewater treatment technologies, it can also be produced from wastewater, and bio-electrolytic conversion is one of the innovative technologies in this direction [36]. A number of wastewater effluents (alone or with other wastes) had been utilized for ethanol production, i.e., OMW and olive pomace [16], apple pomace hydrolysate [68], etc.

4.2.3. Biodiesel

Algal growth in water bodies is an indication of water pollution. However, nutrient rich waste water can be utilized for the production of blue-green algae that accumulate the lipids in it and that in turn can be utilized for the production of biodiesel trough transesterification [69,70]. Algal biomass thus obtained can also be utilized as animal feed and also spread out as fertilizer. Certain species of algae, grown in wastewater is capable of produce oil up to 80% as its storage product and produce more oil, around 23 times more than the best oil-seed plant. In terms of oil produced per unit area, algal productivity exceeds palm oil by 10 bend, and jatropha, canola, and sunflower crops by more than 30 bend [20]. Oil transesterification to biodiesel, algal biomass, and glycerol can be utilized to produce energy products, and glycerol may be used as fuel for burning directly or can be converted to hydrogen and bioethanol by fermentation [71]. The viability of algal biomass for the production of biodiesel can be improved by instant wastewater treatment, use as animal feed, and the production of secondary energy products. Microalgae were also used in phytoremediation of wastewater sources [51].

4.2.4. Biohydrogen

Wastewater may be used through dark fermentation for the production of hydrogen. A microbial consortium contains a wide variety of bacteria, and some of them inhibit hydrogen production (i.e., hydrogenophilic-methanogenesis) by their consumption (homo-acetogens and methanogens) [54]. So, for optimum hydrogen production, the activity of inhibitory microbes gets suppressed or they are killed, either by heat pretreatment of inoculum or by increasing dilution rate and by decreasing the pH of reactors. Another reliable and finely honed process is catalytic methane to hydrogen conversion [72]. Different wastewater and effluent have been used for hydrogen production, these are TxW, PWW, rejected water and seed sludge, MW, OMW, BW, etc. [54,71,73–75].

4.2.5. Biomethane

Methane is another gas produced from anaerobic digestion of wastewater and effluent. Methane can be produced either by hydrogenophilic-methanogenesis (abiotically) or by fermentation of organic matter present in wastewater (biologically) [76]. Anaerobic digestion process is more proficient over aerobic process for production of methane due to low energy rations, high energy production in the form of methane, and low sludge production with high organic ejection rates. Various wastewater effluents, i.e., PWW, brown water, rejected water and seed sludge, sugarcane juice in the effluent discharged from sugarcane industry, etc., have been used for methane production [22,55,77].

4.2.6. Bioelectricity

Bio-electrochemical conversion process is involved in production of electricity from wastewater and effluent, in which catalytic commotion of microorganisms utilize the organic matter and produce the electrons that may be received by cathodes to generate the electricity [57,78]. Organic electron donors are catalyzed for oxidation in the anodic chamber by electrochemical bacteria, and electrons are supplied to the anode, which can be arrested in the form of bio-electricity [79]. In this process, exchange of protons, generated from anodic chamber to cathodic chamber, where these protons are involved in the production of cherished products [69]. Algal biomass, which is generated by photosynthesis, can be a direct organic source of electricity generation in Microbial Fuel Cells (MFC) and for producing biofuels [68].

4.2.7. Syngas

Syngas consists mainly of a mixture of carbon monoxide, carbon dioxide, and hydrogen that can be used as combustion fuel (heat energy value 8–14 MJ/kg or 10–20 MJ/Nm^3), or converted to liquid fuels using a biological or chemical process [80]. Syngas can be used to produce synthetic petroleum through the synthesis of Fischer–Tropsch, or through the gasoline methanol process. Conversely, the anaerobic bacteria can transform the syngas carbon monoxide into ethanol, with average yields of 340 L of ethanol per ton (municipal solid waste, agricultural waste, animal waste, etc.) [81]. The combustion of biomass (or syngas) in the presence of excess oxygen supply results in full oxidation and the production of hot flue gasses usually used to produce steam to drive electric turbines for electricity production with an output of approximately 30% [82].

5. Strategies and Mechanisms for Recovery of Renewable Energy Products from Waste Water

To produce the various valuable energy products from the wastewater, it has to be digested with the aid of a variety of microorganisms to produce the specific type of energy product. Even after digestion, the remaining sludge is treated again with various physical and chemical methods to obtain more energy from the wastewater and it's left over materials. A broad variety of energy products and value-added compounds can be extracted from wastewater effluents; energy in electricity form can somewhat minimize electricity scarcity [77]. There are various techniques involved in the production of energy products from wastewater namely, MFC, bio-electrochemical system (BES), biochemical, chemical, and biological (aerobic and anaerobic digestion of effluent) [58]. The key methods used to produce energy from the waste water are:

5.1. Anaerobic Digestion to Produce Biogas

This is a biological process that involves using microorganisms to transform the organic waste into valuable products. Anaerobic treatment of liquid waste or wastewater provides the ability to rapidly minimize the organic content of the waste while reducing the energy usage of the treatment process and the production of microbial biomass or sludge [29,71]. AD, as shown in Figure 3, is a complex process that involves and carries a variety of reactions (in absence of oxygen) such as hydrolysis, acidogenesis, acetogenesis, and methanogenesis [2]. AD is a very useful process which is applicable on a wide variety of waste effluents (sewage sludge, industrial wastewater, domestic wastewater, etc.) for their conversion to useful products especially into various energy forms, i.e., biohydrogen and methane [55]. The conversion of organic compounds into sludge in wastewater generates a by-product which needs further treatment or disposal. Reduction in sludge and energy consumption are the two attributes which make it economically attractive for municipal and industrial waste streams to consider direct anaerobic pretreatment of wastewater. AD is affected by various factors like temperature (25–35 °C), pH (~7), moisture, carbon source, nitrogen, and C/N ratio [2]. AD of sewage sludge used in treatment plants is very useful now because of lower disposal costs, and it is ecofriendly, too. Direct anaerobic treatment may also provide excess energy for relatively warm wastewaters which contain significant degradable organic compounds [47]. However, even with low-strength wastewaters, the energy savings that can be achieved by avoiding most of the aeration costs are significant. Anaerobic treatment effluents, however, are often not suitable for direct discharge into the receiving waters without further treatment that may require aerobic polishing. Nonetheless, this treatment scheme can be explained by the reduced aeration demand and the production of sludge in aerobic treatment following anaerobic pretreatment. The average ambient temperature of the wastewater has an effect on anaerobic treatment design quality [83]. Some wastewaters of low and medium strength are relatively cool (<20 °C), and the energy needed to heat them to mesophilic temperatures is significant and not economical. Wastewater with a temperature of 20 °C and a COD of 20 g/L, and biogas generation produces around the same amount of energy needed to increase the liquid's temperature to 35 °C. So, treatment at ambient temperatures is only feasible for wastewaters of low and medium strength. Successful anaerobic treatment of wastewater as low as 15 °C is feasible, but application of anaerobic digestion should not be taken into consideration below 12 °C [84]. On the other end, there are many industrial wastewater sources that are very warm and can be considered as mesophilic (food processing) use, and in some cases, thermophilic (distillery waste) anaerobic digestion.

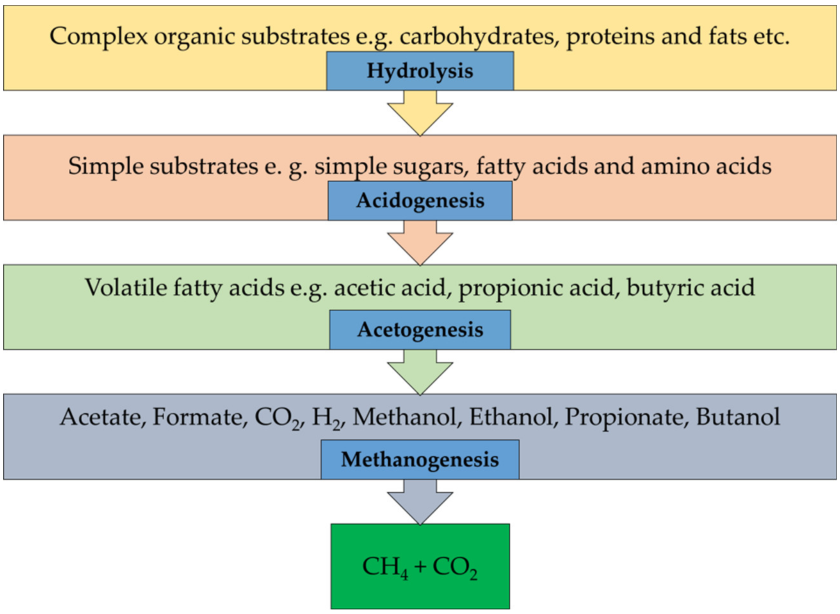

Figure 3. Showing stepwise anaerobic digestion process.

5.2. Fermentation to Bioethanol

It is well known that bioethanol is developed as a renewable liquid fuel. Bioethanol can be used alone or combined with traditional liquid fuels to form either Gasohol or Diesohol. Bioethanol is usually produced under anaerobic conditions through fermentation of simple sugars, such as glucose and fructose. Several yeasts, including, for example, *Saccharomyces* sp., and other bacteria including *Zymomonas* sp., undergo this fermentation [6,50]. A variety of industries, such as sugar, food processing, meat, and pulp and paper, have developed carbohydrate (glucose, fructose, lactose, etc.) rich wastewater that can be converted into bioethanol through fermentation. However, the current challenges are using waste streams in which organic carbon is not present as simple sugars through the use of chemical or biological pretreatment or novel microorganisms that ferment a wider range of organic substrates [53]. Currently, there is extensive work focusing on pretreatment procedures for cellulolytic. The small yields of ethanol obtained in fermentation (typically 10% (*v*/*v*)) currently need subsequent energy intensive distillation. Conventional ethanol plants will expend more than 30 per cent of bioethanol fuel's heat energy during the distillation process [49,85,86].

5.3. Microbial Fuel Cells

Fuel cells transform chemical energy into electrical energy. Microbial fuel cells work using bacteria that oxidize organic matter in wastewater to transfer electrons to an anode from where they pass to the cathode through a circuit to combine protons and oxygen to form water. Electricity is produced by the difference in potential coupled to electron flow [58]. Microbial fuel cells have become an emerging technology and a number of these have been successfully operated with both pure cultures and mixed cultures, which have either been enriched by sediment or activated sludge from wastewater treatment plants [87]. Wastewaters of very different characteristics can be used: Sanitary waste, wastewater for food production, dairy manure, swine wastewater, and corn stove. This technology may effectively use bacteria already present in wastewater as catalysts to produce electricity while treating wastewater simultaneously, but its advancement is hindered by low power output and high material costs. To date, microbial fuel cells have not been used in large-scale applications, but are used to produce energy for BOD sensors, robots, and small telemetry systems [59,88].

5.4. Combustion, Gasification, and Pyrolysis

The heating of sludge in the presence of a small supply of oxygen contributes to gasification and syngas output. In order to generate pyrolytic oil, biochar, and non-condensable gases, combustion and pyrolysis require a fully inert atmosphere at moderate to high temperatures (300–900 °C). Bio-oil can also be used as a liquid fuel or converted into a synthetic gas (CO and H_2), whereas biochar, non-condensable gases, and bio-oil can also be used through combustion to produce electricity and heat [80,89]. Gasification involves the thermochemical conversion of organic compounds through partial oxidation at high temperatures (650–1000 °C) to optimize gaseous products (CO, H_2, CO_2, and light hydrocarbons), particularly synthesis gas (CO and H_2) [81]. Depending on the gasifying agent and temperature, the energy content of the natural gas ranges from 4–28 MJ/Nm. Additionally, the biomass contained in wastewater, such as microbial and algal biomass, and other biomass, can also be gasified into energy products, including heat, steam, electricity, syngas and liquid fuels, and biogas [2,90]. If the heat energy is also captured and combined heat and power (CHP) are given, the output can be improved up to 50% and up to 80%. The viability of applying combustion or gasification has to do with moisture content, and the practical problems of tar formation, mineral content, over bed burning, and bed agglomeration. The feedstock must be relatively dry; with 40 to 50 percent maximum moisture content [82]. Co-pyrolysis of sewage sludge with other non-biodegradable waste such as polythene and plastic waste was also performed at 525 °C in a stirred batch reactor under N_2 atmosphere. This potential synergetic strategy resulted in better yield of H_2 and CH_4 as compared to individual pyrolysis of sludge, and that can be used as gaseous fuel. This combined feasible management provides an alternative for both residues to be generated in a better output [91]. Dryers may be used in the design, but there is a direct trade-off between the amount of energy in the feedstock and the amount of energy spent on drying. Since gaseous and solid phase contaminants are potentially generated from the application of these technologies, there are many possible negative environmental consequences, including heavy metals, dioxins, furans, and NOx gases [92]. However, evidence suggests that technological interventions can control these emissions and use of combined cycle gas turbine, the generated gas can be diverted to various end uses such as direct combustion for heat and electricity generation.

5.5. Incineration of Sludge for Energy Production

Sludge is one of the useful byproducts from wastewater treatment plants predominantly consists of 75% mud, and 25% solid matter, but for any further use, it must be treated to remove the pathogens. The residual sludge can also be used for the manufacture of different energy products from it after wastewater treatment [22,30]. Typically, bio-solids are comprise of huge quantities of water that can be collected by using dewatering machines for further use either as biofertilizer or by incineration for heat and electricity generation. This technique is used by various Municipal Solid Waste (MSW) organizations or waste management firms to dispose of the bio-solids and extract the energy from it to fund their operational expenses [44]. Thanks to its global effect on waste minimization, resource optimization, and renewable energy production, energy recovery from wastewater and sludge in contemporary to wastewater management remains assured. Figure 1 shows the focus energy conversion methods, which shows the sludge conversion pathways to biogas, heat, and electricity. Commercially incinerated bio-solids with several hearth furnaces (MHF) and fluid bed furnaces (FBF) [47,53]. MHF burns bio-solids and allows the hot air to dry incoming bio-solids, reduces moisture, and increases the efficiency of MHF for heat generation, while FBF is a modern and efficient technology that provides continuous operation without any multi-stage device that eventually increases the efficiency of the overall process and technology of incineration [93]. Residual gas pollution is a challenge in both of these incineration technologies, but can be addressed with the use of advanced scrubber systems to make these technologies more efficient and environmentally friendly [94].

6. Advancements and Integrated Technologies to Recover Energy Products from Waste Water

Anaerobic wastewater treatment is currently the most commonly used method for extracting energy from wastewater. The energy is harvested as methane production. Removal of the energy lost due to heat dissipation during energy conversion from different reducing matters to methane, energy consumption to sustain microbial activity, and residual reducing matters of wastewater after treatment, 80% of the chemical energy found in the original reducing matters can be transferred to methane [24,95]. In view of the fact that only about 35% of methane's chemical energy can be converted into electricity through the combustion cycle, the overall efficiency of energy recovery is about 28%. If more efficient CH_4-driven chemical fuel cells are created, this number will theoretically increase to 40%. Our future perspectives should be production of more and more energy products to minimize the cost of overall wastewater treatment processes [43,75]. While streams and technologies can be matched individually, the integration of technologies and waste streams holds the greatest promise in achieving long-term energy security while maximizing wastewater treatment. There are many examples where this worked. Thus, our aim should be to design an approach in such a way that wastes that we generate can be reconverted into pathogen free resources without any cost and without polluting our environment. Some of the steps which may be taken are as follows:

6.1. Scale up of MFCs

MFCs utilized now are designed for lab scale purposes, but to know the utility of MFC, these should be scale up to a practical level so the energy recovery can be enhanced and optimized [57]. The restriction in scaling of MFCs are high scaling cost, pH buffers, high internal resistance, high material cost, and low efficiency of mixed cultures on an electrode and these limitations may be overcome by reactor engineering, biological employment and material development [63].

6.2. Digitalization of Process

The parameters and techniques used in a process should be monitored to an extent to achieve a high yield of by-products and chemical compounds from the treatment of wastewater and effluents [12]. In case of electricity generation electro-chemical parameters, i.e., electric current, indicators, and electrode potential, are some useful parameters which can be monitored for optimum electricity production [37,68].

6.3. Statistical Modelling

More optimization of the process may be obtained by the use of mathematical models, especially two directional. Use of these models facilitate the complex process and make it easy to perform at a practical level rather than lab scale [64,95].

6.4. Multilateral Approach

In the hybrid approach, more than one useful product is produced in a single process, for example, integrated hydrogen and methane production, this leads to recover maximum energy from wastewater [96]. MFC coupled with anaerobic membrane bioreactor and integrated photo-bioreactor is a game changer for this energy recovery from the wastewater [66,69]. This technique is capable of treating high levels of wastewater along with polishing treatment for removal of specific pollutant types from the effluent.

6.5. Use of Genetically Modified Microorganisms

Energy generation by wastewater treatment can also be improved by selection of the best microbial species responsible for specific biofuel production and specific pollutant removal; this will lead to reducing the operation costs and energy consumption for the process [62,97].

6.6. Hydrothermal Carbonization of Sewage Sludge

Hydrothermal carbonization (HTC) is a thermochemical process that can be used as a solid fuel or soil conditioner to transform liquid biomass into so-called biocoal. HTC can be an alternative to anaerobic digestion or a supplement in sewage sludge treatment. In the latter case, digested sludge serves as feedstock to HTC [98]. In 2010, the first industrial plant in Germany (Karlsruhe) was built in a WWTP. HTC's benefit is almost complete recycling of organic matter, very strong dewaterability of the resulting sludge, and an increased energy balance [99]. HTC is a recent, on the market technology, although the process has been known for over a hundred years. It is conceivable that HTC will develop into a standard sludge treatment technology in the future.

6.7. Integrated Algal Biodiesel

Historically, algal biodiesel has been suggested to be financially feasible only with concomitant wastewater treatment or animal feed production, valuable secondary products, or supplemental energy products. More recent analysis shows that recovery of algal biodiesel from wastewaters can be beneficial after 2 to 4 years with a fair breakeven [40,100]. There has been a lot of speculative interest in algal biodiesel recently, which had been fueled largely by the increased price of diesel before the reversal in 2008. Many new companies have been set up to use algae to develop biofuels and to obtain certified emission reductions (CERs) by reducing CO_2 (IGV GmbH, Nuthetal, Germany, undated) [35]. One example is Aquaflow Bionomic (Nelson, New Zealand), which reported harvesting crude oil to refine it into paraffinic kerosene for use as jet fuel, from wild algae grown on oxidation ponds used in the domestic and agro-industrial waste stream treatment trains. Within a 60 ha facility, this plant treats 5 billion liters of water per year [101]. More innovations will show whether these ventures are financially viable and will be introduced not for demonstration purposes, but for growth.

6.8. Advanced Integrated Wastewater Pond Systems

These consist of an anaerobic digester and algal pond with high concentrations. For nine years, a facility in Grahamstown, South Africa, has been tested for effectiveness in wastewater treatment. Nutrient and organic removal levels were reached comparable with traditional wastewater treatment works and negligible *E. coli* counts [24,50]. Anaerobic digestion biogas provides energy, and the algae may be used as fertilizer or fuel (e.g., biodiesel). Despite these and many other international examples of wastewater energy projects, in many countries there is no overall view of the potential or a plan for harnessing this renewable energy source. Anaerobic digesters are used by many urban wastewater treatment plants as part of the wastewater treatment process [76,102]. Although some use heat internally to control digester temperatures and to heat building space, however, the majority vent or flare the gas. This shows the weak integration of energy usage and the potential for reducing greenhouse gas emissions have not been understood [103]. Wastewater treatment plants must be integrated to use biogas to dry and pellet the wastewater sludge, thus reducing the on-site disposal costs and environmental burdens while providing a potential source of energy. The pellets have an energy content of ~16.6 MJ/kg and were used as additional fuel in their kilns by a local cement factory [99].

7. Benefits of Using Wastewater for Energy

Examples of where energy is extracted from wastewater to produce a range of energy products at varying scales (from small rural to large industrial operations) exist worldwide. A limited range of examples to demonstrate the energy potential from wastewater technologies is presented.

7.1. Domestic Biogas

In 1975, the Chinese government began a household biogas mass implementation strategy. Units were being installed within a few years at a rate of 1.6 million per annum. The technology continued to be developed and implemented, and in 2005, China had 17 million digesters generating 6.5 billion m^3 of biogas per annum [11,27]. Importantly, one fifth of households in rural areas get electricity from biogas. In India, Nepal, Vietnam, and Sri Lanka, this trend of rapid installation of biogas units has repeated itself. There are currently more than 2 million family-sized units in service in India, and over 200,000 families move from the traditional fireplace to cooking and heating biogas per year [2].

7.2. Biogas for Agricultural Use

Meili village (province of Zhejiang, China) slaughters 28,000 pigs, 10,000 ducks, 1 million ducklings, and 100,000 chickens each year, and the wastewater is fed to an anaerobic digester that generates enough biogas for more than 300 households and 7200 tons of organic fertilizer each year (ISIS, 2006) [2]. A similar process is used in Linköping (Sweden), where the biogas is upgraded to vehicle fuel standard for all public transit vehicles in the city (>60 buses), converted to run on biogas in 2005 (IEA Biogas, undated) [104]. Throughout Ireland, wastewater from farms in Ballytobin and the food processing industry produce electrical and heat energy by anaerobic digesters for the local farming population. With gas turbines and combined heat and power, this plant produces an additional 150,000 kWh of electricity and 500,000 kWh of heat energy per annum (IEA Bioenergy, undated) [91].

7.3. Bioethanol

A few examples of wastewater and wastewater sludge use for bioethanol production have been published. Finland's VTT Technical Research Center has developed technology for distributed ethanol production by fermentation of food processing wastewater. This technology allows production even on a small scale and is estimated to be capable of meeting 2% of the total volume of petrol sold in Finland, and is currently being marketed by St1 Biofuels Oy [38,48].

7.4. Energy Production

To sustain rising populations and expanding cities, the planet needs more resources. The use of waste for energy for many cities is an inexpensive, sustainable, and readily available source of energy. Because sewage treatment plants can use biogas generated from their own sludge to power their operations, they can be self-sufficient in energy. It means that the primary purpose of a sewage plant-eliminating toxins and disease-causing pathogens is not disrupted by power outages [9,15,31].

7.5. Emissions Reductions

Methane accounts for 16 per cent of global greenhouse gas emissions, and it is very strong—about 30 times more powerful than carbon dioxide, a greenhouse gas. Sludge-to-energy systems harness this methane for energy instead of allowing it to escape into the atmosphere where climate change will be fueling. Although methane releases carbon dioxide when harnessed for energy, if methane-rich biogas is used instead of fossil fuels, the net emissions are negligible [35].

7.6. Waste Management

Many developing countries lack the infrastructure necessary to manage solid waste and sludge properly. Such toxic, foul-smelling waste is frequently dumped directly onto land or surrounding waterways in these areas, where it can threaten public health. For example, in China, more than 70 per cent of urban solid waste and sludge are landfilled or dumped—sometimes illegally. One alternative is a sludge-to-energy strategy [91,105].

7.7. Economic Benefits

Sludge-to-energy systems reduce the need for more costly and polluting power sources, such as fossil fuels. However, those who run waste-to-energy operations will directly benefit from selling the gas and solid digestate [54].

8. Barriers in Recovery for Renewable Energy from Wastewater

The interrelationship between energy and organic wastewater content should facilitate energy recovery operations from different sources, including wastewater treatment plants wastewater [106]. Combining the anaerobic digesters with biosolid incineration for electricity generation from wastewater utilities will reduce energy consumption through 5 to 85 per cent [83]. But still there are many challenges that must be took in consideration for efficient utilization of wastewater to transform it into energy related products and other valuable products. Recovery of energy from the wastewater depends upon its organic content, and any deviation in it further adds to uncertainties in its utilization in the reactors for energy production [105]. Low temperature is another crucial challenge in the operation of anaerobic digesters because most of the microorganisms work in ambient temperatures, i.e., 15–35 °C and if there is any change from this range, the organism will not work efficiently and the kinetics of overall process falls down and reduce the production of energy components, i.e., CH_4 and H_2 [65,100]. Additionally, it will make it difficult to perform the anaerobic digestion to produce the valuable energy products from the wastewater. Wastewater is mainly composed of different organic materials and nitrogenous wastes. Almost all biodegradable matter in wastewater is converted into methane, but there is the chance of forming nitrous gas (potent greenhouse gas) during the partial nitration process from the nitrogenous wastes, and it may also reduce pH and oxygen levels that are important for survival of various microorganism inside the digester [2,107]. Sometimes phenolic substances are inhibitory to microbes, and great care should be taken in the selection of microbes for production of desired energy products. Moreover, the complexity of wastewater due to the introduction of new chemicals and substances from various anthropogenic activities is another growing challenge. Such activities not only change the uniformity of wastewater, but also make energy recovery from wastewater an uphill task [108,109]. Potential barriers to hydropower generation at wastewater treatment plants include a lack of excess heat, flow rate variations, turbine failure due to blockages, or particulate matter present in wastewater, especially in raw sewage. A resource recovery process is not cost effective due to excessive operational cost. While various technologies have been explored in the academic arena for the recovery of water, electricity, fertilizers, and other wastewater products, none of these have ever been implemented on a large scale because of technological immaturity and/or non-technical bottlenecks [110]. In order to treat wastewater more effectively and recover the essential energy-related products, all these problems and concerns have to be tackled in a very comprehensive way in order to solve all the wastewater-related issues besides developing more efficient and ecofriendly technologies.

9. Conclusions

Although domestic wastewater cannot completely satisfy the industrialized society's energy demands, it is a valuable resource that should be widely exploited and used in the future. Wastewater these days is no longer wastewater, however, most of agencies look at it as a resource rich in organic content and minerals. These all components could be utilized for the production of renewable energy products or to grow plants and algae that later on can be converted to various types of biofuels as per the requirement. The complex nature of effluent and wastewater make it difficult for the existing technology to remove all the pollutants effectively. So, there is an urgent need to develop a combined strategy using biological, chemical, and physical processes to treat the wastewater as well as to recover valuable products from this untapped resource. Using some of the advanced technologies like membrane bioreactors can be useful, but these have higher operation and maintenance costs compared with conventional processes. Moreover continuous efforts should be there on the development of suitable consortia that not only work on variable conditions, but also help to recover the valuable products from the wastewater. Despite all these facts, on one hand, there is a need for strict discharging standards to be implemented, and on the other hand, researchers and the scientific community need to develop the cutting-edge technologies to recover all the desired products in a sustainable manner.

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