Chapter 8
Bioelectrochemical System for Wastewater Treatment for Energy via Suitable Microbial Systems

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Abstract Wastewater treatment with capacity of trillion of liters is reported to spend a billion of Euro currency with some amount of energy. Now, it can be utilized as renewable organic matter resources for production of electric power, hydrogen and caustic soda chemicals with saving of more amounts of money and energy.

Bioelectrochemical system is utilized for synthesis of electricity power or hydrogen biomolecules or chemical products via application of microbial fuel cells (MFCs) or microbial electrolysis cells (MECs) that are used for the chemical energy of waste organic matter from low strength stream of wastewaters or lignocelluloses biomass. And microbes are worked as catalyst with utilization of different types of organic compounds without need of expensive metal as catalyst. This system helps in breaking down of complex organic in wastewater system via electrically active microbial cell application with cleaning of wastewater system. New useful products formation is reported from microbial electrolysis process in bioelectrochemical system with recovery of nutrients and metals or removal of toxic and recalcitrant compounds. Microbial fuel cells are used for synthesis of hydrogen fuel. European Union has started with many innovative projects for wastewater treatment with acylamine function amine function of carbon anode for improved or enhanced microbial electro-catalysis. Improvement in environmental and energy performance has reported via wastewater treatment with biochemical or biofuel production. The author will discuss the new concepts and invention of alternative materials development for electrode, separator, or catalyst and also innovative design for bioelectrochemical system with emphasis on recent development for electric power or other products formation with its limitations.

Keywords Bioelectrochemical systems · Biofuels · Microbial systems · Wastewater · Treatment · Anode · Cathodes

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Abbreviations

AD	Anaerobic digestion
AM	AM radio waves of 540–1600 kHz
BES	Bioelectrochemical systems
BMP	Biochemical methane potential
BOD	Biological oxygen demand
CH_4	Methane
COD	Chemical oxygen demand
CSIR	Continuous stirred tank reactor
EPA	Environmental Protection Agency
HWW	Hospital wastewater
IC	Internal circulation
IPB	Integrated photo-bioelectrochemical
LDP	Loss of dairy product
MEC	Microbial electrolysis cells
METs	Microbial electrochemical technologies
MFCs	Microbial fuel cells
NAC	Net anodic compartment
OTUs	Operational taxonomic units
PCR	Polymerase chain reaction
PHCs	Petroleum hydrocarbons
PPW	Petroleum produced water
PW	Pure whey
SBR	Sequencing batch reactor
SCIE	Science citation index-expanded database
TAC	Total anodic compartment
TDS	Total dissolved solids
TNT	TiO2 nanotube
TS	Total solid
TS	Total solid
TW	Tera Watt
VFA	Volatile fatty acid
VS	Volatile solid
WHO	World Health Organization
WTE	Waste to energy
WWTPs	Wastewater treatment plants

8.1 Introduction and Basic Concepts

Suspended solids, various types of nutrient substrates, biodegradable plastic or other organic matter, microbial pathogen, toxic heavy metals, refractory organic compounds or other dissolved inorganic matter or solids are reported as contaminant in wastewater stream (Souza et al. 2018). Wastewater stream is good source of refractory organic compounds which are agricultural pesticides, surfactants, and phenols and they create big challenge as exhibiting the resistance toward conventional nature of wastewater treatment methods. Heavy toxic metals as major contaminant come from waste generated by commercial or industrial activities. Waste products from these places are reported to deposit in water bodies and become polluted domestic water or wastewater resources containing inorganic solid, Na^{+}, Ca^{+}, or SO_4^{2-}. This wastewater contained various types of biodegradable organic compounds including carbohydrates, protein, or fats. Biodegradable organic matter can destabilize the natural oxygen in the river, pond, or other ecosystem. Discharged wastewater into lakes and stagnant waters are needed to go for proper treatment (Taha and Al-Saed 2017).

Bioelectrochemical system can be a new technology for wastewater with improved efficiency for energy synthesis. For this application some limitations for BES anode electrode are found for not directly discharging electron via using wastewater effluents. But this problem has solved BES cathodes with enhanced treatment for additional selected contaminants (Gul and Ahmed 2019). Investigation for a number of effective approaches is reported that grouped the cathode-supported waste or cathode-stimulated treatment for waste matter. Cathode-stimulated treatment is proceeded with involvement of electron transfer facility directly with reduction of various contaminants (nitrate or dye removal). But cathode-supported treatment approach is completed with contamination removal that utilized aerobic oxidation, algal biomass growth, or strong oxidant generation in advanced oxidation approach or membrane supported treatment (Kaur et al. 2018).

This BES system is operated at mild conditions with microbe's involvement (responsible for electron transfer from an electron donor of lower potential value to electron acceptor of high potential). In this process, at anode site the oxidation process takes place whereas at cathode site, electrochemical reduction processes take place and result in other products formation at this site (Jain and He 2018).

Seven units of full scale biological wastewater plants are discussed with their location identification at the Polar Arctic circle region in Finland. These places are reported with archaea, bacteria, or fungi as potential community's structure that can be utilized in bioreactor operation. Different analysis approaches such as quantitative PCR, massive parallel sequencing, or multivariate reduction are applied for identification of respective genes or pathways of respective microbial system and these approaches can help in effective wastewater treatment in bioreactors. These biological approaches can help in activated sludge system. Activated sludge system is a strong source of effective and dominated bacteria compared to archaea or fungi species that are confirmed by diversity analysis approaches (Cydzik-Kwiatkowska and Zielin 2016).

A core operational taxonomic unit (OTU) in influent feed and bioreactor is reported. Several microbial strains such as *Methanobrevibacter*, *Methanosarcina*, *Thamumarchaeota Trichococcus Leptotrichiaceae* (archaea), *Methylorosula* (bacteria), or *Trichosporonaceae* (fungi) are reported as dominant organisms. Oligotype structure of core OTUs is reported with ubiquitous fungi type oligotype in sewage influent and bioreactors both. For these (i.e. above mentioned microbial species) microbial system confirmations, multivariate redundancy analyses performed for core OTUs, related organic or nutrient matter removal. Competition among archaea or fungi species is reported in OTUs. And bacteria species in OTUs are positively correlated at extremely cold temperate operated bioreactors (Gonzalez-Martinez et al. 2018).

On a daily basis, wastewater generation is reported from domestic or industrial sources all over the world posing the water crisis and environmental deterioration as big challenge for society. Developing of sustainable energy from efficient ways of wastewater treatment plants can provide best solution for energy shortage issues in everyday life and success is possible with the help of recent advance in microbial electrochemical (MEC) technology development (Krieg et al. 2014). MEC technology can help in wastewater treatment as well as synthesis or recovery of clean energy with usable water purification. Various types of designs and configurations of MFC units can help in treatment of wastewater organic matter. In addition, they help in treatment of waste matter, come or desposited, from domestic or industrial activities. This process needs indigenous or enriched electrogenic microbial system including some fungal or bacterial species. Design performance improvement has reported by using conventional or simple nature single chamber or dual chamber MFCs unit to integrated hybrid or engineered MFCs units via application at lab scale to pilot scale level. These MFCs design has applied for wastewater treatment with more amounts of electric power and clean water generation via removal of toxic or waste organic compounds (Krieg et al. 2014; Rathour et al. 2019).

A tubular shaped, single chambered MFCs unit in continuous mode has generated high power outputs. Granular graphite matrix anode electrode with ferricyanide solution containing cathode is reported to be effective wastewater treatment with energy generation (maximum power outputs). MFCs system with 66 or 90 W m^{-3} as maximum power outputs is reported for net anode compartment (NAC) but 38 or 48 W m^{-3} power outputs is found at total anodic compartment. For digester effluent and domestic wastewater, feed streams are reported to contain acetate or glucose as organic matter and is reported to generate power output of 59 and 48 W m^{-3}, respectively, at NAC. Total Coulomb conversions efficients are 75 and 59% for acetate and glucose, respectively, with loading rate (1.1 kg COD m^{-3} NAC volume/day). Improved MFCs performance enhanced the conversion of non-rapid biodegradable organic matter with better facility of direct electron flow from anode to cathode electrode. Sustainable and open air cathode has shown critical issues for its practical implementation in MFCs (Rabaey et al. 2005; Blanco-Aguilera et al. 2019).

Conversion of waste nature matter to energy fuel (WTE) technology is reported and incineration process, AD (anaerobic digestion), pyrolysis, and gasification are good examples of WTE but they suffered from low efficiency with high energy needs. MFC technology is applied for production of renewable or sustainable energy sources with more opportunities for current period global energy crisis problem. In India, the total wastewater generation is reported almost 250% or more with least or minimal total treatment capacity (Pan et al. 2015).

Government is putting efforts on developing sustainable mode of solution for degradation or treating of waste matter and world human population is reported to consume seven billion cubic meter of water quantity every year with further rise these value to 950 and 1422 billion m^3 in coming periods (year 2025 or 2050). Wastewater treatment is a big or critical challenge with serious concern or problem and it can provide more amount of energy recovery potential. In this regard, MFC technology would be generated nearby 23.3 or 40 terawatt (TW) power in year of 2025 or 2050, respectively, via achieving proper wastewater treatment with simultaneously generation of electric power throughout the urban areas of India (Khan et al. 2017). Bioelectrochemical systems (BES) have shown their potential with capability of performing the simultaneous mode of wastewater treatment and electricity or fuel energy or valuable biochemical synthesis. Performance evaluation of global level scientific outputs of BES related research is reported on more research publication or papers in science citation index database (SCIE) from years 1991 to 2014. Further, published in journal as an output in subject categories is found in countries and institute analysis on BES design or configuration in world research works also reported. More number of annual publications on BES design or operation are now increased steadily after the year 2004. MFCs system is studied as bioreactor or devices for electric power synthesis with wastewater treatment tasks as dominant or broad applications. Carbon nanotubes and grapheme have been reported as nano-structured materials in the BES field (Wang et al. 2015). The author will emphasize in this chapter on recent development on wastewater treatment via various designs of BES with more efficiency for clean energy generation.

8.2 Wastewater Sources and Its Components

Wastewater is generated due to various human activities at domestic or industrial level and it contained liquid waste matter from various sources and people from domestic or homes, agriculture, commercial. Pharmaceutical sectors with hospitals sites are principal sources for wastewater generation. Hospital wastewater (HWW) has reported to contain pharmaceutical wastes or residues, hazardous chemicals matter or pathogens as well as radioisotopes as dangerous substances. They create different nature of risks (physical, chemical, or biological) for public or environment components health issues and currently, without any legal procedure for effluent treatment in hospital sites prior to discharge into municipal side collector or directly disposed onto surface water sources (Carraro et al. 2017).

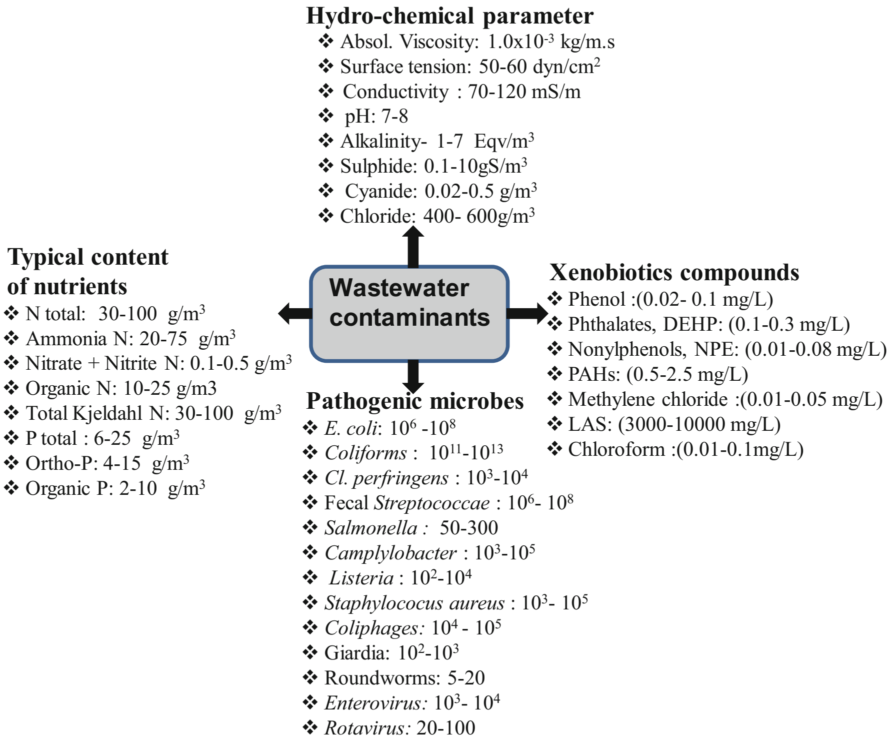

Fig. 8.1 Contaminants in wastewater from different activity of society (Henze 2008)

Hospital wastewater (HWW) is full of hazardous substances and pharmaceutical wastes or residue, chemical nature of hazardous substance or compounds, pathogens and radioisotopes are main contaminants. To minimize the adverse effects, these compounds need to be neutralized by wastewater treatment plants (WWTPs) (Wang et al. 2020). Wide ranges of concentration for hazardous contaminants is reported due to depending on the size of a hospital or bed density, numbers of impatient or outpatients crowd rate. Further, number or types of wards or services and seasonal effects of country also affected the contamination risks. Some hazardous substance come from dental amalgam or medication and these are also produced in hospital facilities and follow to regulatory status, proper treatment for different types of wastes is done before dispose to environment (Carraro et al. 2016) and shown Fig. 8.1.

Role of hospital wastewater is reported for environmental contamination and different legislation around the world are needed for main principles on the hospital wastewater treatment. Guidelines from WHO and EPA guidelines for radionuclide hazard have discussed with guidelines of legislation side for proper disposal of hospitals wastewater to the environment. Biological wastewater treatment processes can be preceded via exploitation of the concerted microbial activities with microorganism's communities' structure that linked to changing at environmental conditions. Development of optimal biological system is reported in engineered microbial system and this engineered microbes development can be done by application of molecular techniques. This technique can help in inadequacy of culture dependent methodologies for identification of microbial diversity in sludge samples (Kassem et al. 2020). Culture independent technology and application of omics in wastewater system can help in understanding of microbial strains diversity and their functions in wastewater treatment processes (Ferrera and Sanchez 2016).

Industrial wastewater is reported to vary great extent in flow rate and pollution strength and it is very difficult to determine the fixed values for industrial wastewater constituents. It is reported to contain various nature of suspended, colloidal, or dissolved solids (inorganic or mineral and organic compounds) that exhibited either excessively acidic or alkaline pH conditions (Choudhary and Parmar 2013). High and low concentrations of colored waste matter are reported with their nature of inert, organic or toxic nature materials with containing of bacterial, Industrial wastes are discharged into sewer system with exhibiting of negative effects on treatment efficiency or undesirable effect on the sewer system (Panagopoulos et al. 2019). It is necessary to proceed proper pretreatment for the waste matter nature prior to release into municipal system. It needs fully treated waste before disposing directly into the surface or groundwater systems (Das et al. 2012).

Wastewater is now reported for good resources of organic nutrients than as a waste mattes, that utilized for plant nutrient and also for energy generation. Generation of energy is obtained from wastewater organic matter degradation. And nitrogen organic matter and P containing nutrient is essential and is utilized for biofertilization. Due to high cost of energy consumption in synthetic fertilizers synthesis, MFCs can provide direct biological conversion of organic matter from wastewater resources into electric power. And significant improvement for this conversion process is reported with competitive to anaerobic digester (AD). The anaerobic mode of biological conversion processes is also utilized for biofuel production which in turn is used for renewable fuel nature electric power generation. Membrane coupled with complete anaerobic treatment system is applied for net generator of energy for larger quantity of consumer energy needs today (McCarty et al. 2011; Gosset et al. 2020).

Municipal and industrial origin wastewater has exhibited high levels of toxicity condition for aquatic life or biotic components and proper treatment is necessary for waste matter before discharged into natural ecosystem in developing countries. Physical, biological, and chemical methods have been employed in water treatment plants in most developed nations and helped in cleaning the wastewater resources. During the effective treatment, each step is analyzed using bioassays and compared to toxicity extent of the input wastewater matter. Industrial origin wastewater is reported to be more toxic in nature and its proper treatment needs to be ensured before sending to municipal wastewater treatment plants. Due to high sensitivity, fast response time and case use and bioassays are employed to monitor progress of each step in wastewater treatment processes in order to provide early warning periods (Donde et al. 2018). Several types of bioassay are conducted in most cases with good comparison capability and high sensitivity (Hader 2018).

Phototactic green algae (*Chlamydomonas reinhardtii*) are reported to generate photoinduced channel rhodopsin-mediated current flow across the cell membrane that is measured by a simple population assay. Process modification of instantaneous measurements is reported due to phototactic degree and orientation of gravitactic attraction. And addition of heavy toxic cations or organic nature polluting agents can rapidly (in one or several minute time) change the photocurrent movement. Opened route of the flagella mediated voltage gate for calcium ion channels can be sensitive routes to the tested heavy metals cations (Chan et al. 2019).

Photoreceptor currents are generated by channel rhodopsins and sensitive capability of photocurrents to heavy metals cations side is several fold more than detected by swimming velocity technique or other physiological parameters of flagella containing algal species. Measurements of photoelectric flow in algal species suspension are ideally suitable options for low cost process with detection of contamination in water due to heavy toxic metal (Govorunova and Sineshchekov 2018).

Wastewater is reported as a combined form of water carried waste that is come from residences or institutions. It also contained waste matter that is created by commercial or industrial activity, which can contaminate the water from underground and surface water (storm water). Municipal, agricultural, or industrial origin or generated waste matter is reported as categories of wastewater sources (Donde et al. 2018). Municipal wastewater can be generated from residential, commercial, or institutional activities and also contained wastes with water from street drainage or runoff sources (Almeida et al. 1999). Commercial or institutional activities can generate more volume of wastewater that comes from hospitals, clinics, departmental stores, offices, or public recreations. Contaminants of wastewater resources are reported with various nature of suspended solids, nutrients, biodegradable nature or pathogens, heavy metals of toxic nature, and refractory organics or dissolved inorganic solid compounds. Ca^{2+}, Na^{+}, or SO_4^{2-} ions in most domestic supplied water are reported and are also shown in Fig. 8.1. Proteins, carbohydrates, and fats as contaminants of wastewater can destabilize natural oxygen in the ecosystem (Hu et al. 2007; Gosset et al. 2020).

Agricultural wastewater includes fertilizers and biomass wastes (animal or cattle dung, tree branches, vegetation fumes, or other agricultural residues). Industrial wastewater contained complex nature or type of waste matter. Waste treatment or selection of the best treatment type or process can be reported in combination of effectiveness and cost (WERF Report 2003; Kassem et al. 2020). Agricultural or industrial waste matter treatments are more complex and are to be treated separately or individually in the concerned premises. Municipal water wastes are generated from wastes with water from cities or urban centers. Solid wastes and sewage are found from municipal wastes and wastes in rural villages are made up of fecal or urine (excreta) feces and urine (excreta) and refuse is done for the garbage or rubbish waste matter (Henze 2008; Wang et al. 2020).

Municipal solid waste matter includes rubbish or garbage fraction from residences and food wastes. Municipal solid wastes include rubbish or garbage from

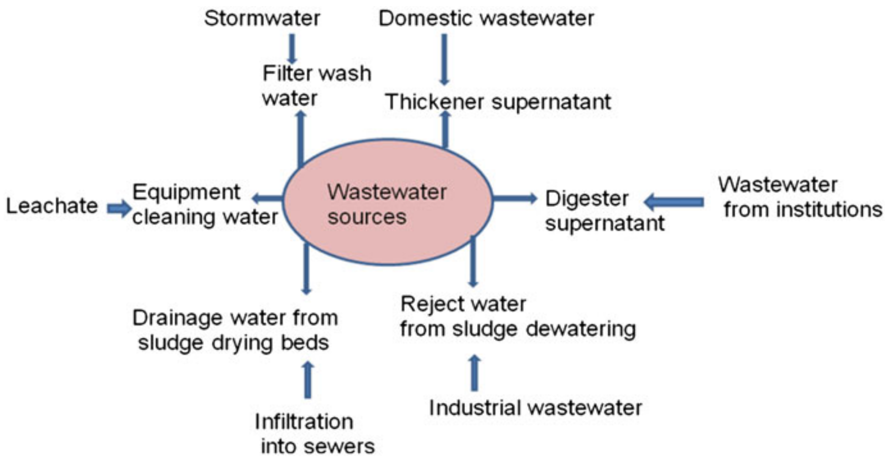

Fig. 8.2 Wastewater generated internally in various treatment plants from society (Henze 2008)

residences and food waste, papers, plastic bags, or glasses from commercial and other institutional centers. Centers are shown in Fig. 8.2. Harmful chemicals from hospitals and commercial centers are reported and need to separately sort with disposition of this waste with special care. Solid waste fraction can be incinerated and also put or keep into landfill sites (Blanco-Aguilera et al. 2019). Sewage organic matter is human excreta and wastewaters are flushed along sewer pipes. Waste matter from kitchen sink, bath, toilet flushes, laundries, and runoff water are needed for sewage treatment. Domestic sewage is contained 99.9% and 0.1% impurities and suspended, colloidal or dissolved solid proportions with gases, pathogenic microorganism and other materials are reported (Roeleveld and van Loosdrecht 2002). There are reports on some wastewater treatments for wastewater cleaning, generation of energy or valuable products as well as solving environmental issues.

8.3 Anaerobic Treatment for Wastewater

Anaerobic wastewater treatment has been applied for two effluents (containing pure whey ~PW) components or loss of dairy product ~LDP) generated from dairy cooperative and methane production was reported. These effluents are found to rich in organic matter (97% for LDP and 87% for PW) and microbiological analysis has shown to obtain the germs and lactic acid bacteria in effluents (Gul and Ahmed 2019). Total coliforms are presented only in LDP and the sulfate-reducing bacteria are absent in both substrates. Low loads (25% and 50%) have reported best CH_4 yields in PW (25.546 ml STP/gVS) and LDP (79.1 ml STP/gVS), confirmed via biochemical methane potential (BMP) assay at 38 °C. Reduction of the volatile solid

(VS) and total solid (TS) is reported more than 80% from two effluents with decrease of organic pollution also (Lhanafi et al. 2017).

Mechanical treatment is used in dairy waste treatment. It proceeded with screen, grit chamber, skimming tank or primary sedimenting process tanks or clarifiers. Chambers are applied for removal of heavier inorganic matter (i.e. sand, grit, or others). Skim processing tanks helped in removal of oils, grease, wood pieces, fruit skin, etc. (Kaur et al. 2018). Settling tanks or clarifier equipment can permit the matter fraction at low velocity rate or at rest parts of sedimentation tanks to settle down at the bottom region of sediment processing tanks. Collection of materials at bottom is sludge organic matter and sludge or effluent fraction is needed for additional treatment for making it harmless nature compounds (Sengil and Ozacar 2006; Kolhe et al. 2009; Kaur et al. 2018).

Comprehensive manner of dairy volarization model is applied as decision support tool for midterm allocation of raw material waste from final products or during production periods. This developed model can help in identification of optimal concentration of product portfolio composition via allocation of raw milk products to most profit gained dairy products (Wazed et al. 2010). This model can help in important constraints identification such as recipes details, composition variations, dairy products formation, interdependencies level, season changes, demand or supply capacity, or flow rate of transport facility This developed model has been analyzed at the international level dairy processor centers (such as Friesland, Campina, or the Netherlands) (Souza et al. 2018). The model structure and its output elements structure are considered to optimal level volarizing the raw products. Comprehensive study and functional nature of this model can be tested the effect of seasonal change on milk volarization process for profit and a shift in the allocation of milk (Banaszewska et al. 2013; Wazed et al. 2010).

Practical or experimental application of biotechnological waste processing or treating of milk production plants is achieved by development of a process for biogas production with application of anaerobic bioreactors. Laboratory scales installations of these reactors are conducted at laboratory studies (Wang et al. 2020). Principal technological scheme of biofuel production is carried out at appropriate material, technical, or economic calculations. Using the information on produced biogases as fuel energy is reported at boiler system with reduced natural gas consumption as well as cost of recycling processes at dairy industry plants (Panfilova et al. 2016).

Anaerobic condition methane from fermentation has found to complete in four steps. And its first step involves the enzymatic hydrolysis of undissolved complex organic compound into simpler or monomer dissolved substance and its second is proceeded with acid formation and also release of short chain volatile fatty acids (VFA), amino acid, alcohols and H_2, CO_2 molecules (known as acidgenic step) (Kassem et al. 2020). And its third step is started with acetogenic steps for conversion of VFA, alcohol and amino acids into acetic acids, dissociation into hydrogen cation and acetate ions where its fourth step is started with methanogenic stage for generation of methane from acetic acids and also result in the reduction reaction of CO_2 by H_2 molecule (Goblos et al. 2008).

The precipitation process is chemical treatment for wastewater treatment and it is completed by adding flocculants (flocculating material) to wastewater and mixed vigorously ad agitators. Precipitation is occurred for insoluble phosphate ions in form of fine particles aggregation into large size flocks formation. Sedimentation basins are continuously scraping the sediment into sump or oblique gutter sites and it carried off-water from clarifier surface layers (Kushwaha et al. 2011). Biological treatment provides benefits via performing the microbial strain mediated transformation of complex organic compounds as well as possible adsorption of heavy metals with the help of suitable microbial cells system. Biological modes of treatment of milk waste treatment are carried out by combining different types of scheme or strategy of biological mode for selective nature of constituent removal (Sengil and Ozacar 2006).

8.4 Bioelectrochemical System (BES) and Its Operation

Petroleum industry application is reported as one of the biggest and fast growing fuels with waste producing industries that is fulfilling the continuous increase of fuel sources (for energy) demand as a form of non-renewable energy nature. Petroleum refinery is reported to produce huge quantities of different types of waste organic matter (oily sledges, huge wastewater, volatile nature organic matter, non-usable catalysts, heavy toxic metals, or others) due to its huge quantity and continuous operation modes in many other refinery operation (including dairy processing units) and it has shown big challenges or issues for managing of huge quantities of generated or produced waste matter from its different petroleum industries processes (Kassem et al. 2020). This industry has generated the complex nature of wastes with the report of changing stringent environmental regulations. This waste quantity can be decreased with reduced energy loss via treatment with conserving the energy loss with utilization of accumulated energy in chemical bonds of these waste organic matter. BES is considered as an efficient tool for reduction of waste disposal with economic benefits via transformation of waste organic matter into energy pool sources. Feasibility of using BES operation has shown more potential alternative for harnessing or generating the huge energy quantity from different waste matter degradation from various petroleum refineries (Srikanth et al. 2018).

It has reported that oily sludge is found as significant solid fractions of waste generated during different types of processing in petroleum industries. This waste is found as complex emulsion of various nature of types of petroleum hydrocarbons (PHCs), water, heavy toxic metals, or solid particles and are reported as hazardous compounds with huge quantities generated at world level. It needs an effective treatment with widespread attention. This waste has shown many negative environmental impacts and many effective treatment methods have been employed for neutralizing this waste with PHCs before its oil recovery or sludge disposal. In this waste, various heavy metals need to treat properly before oil recovery and sludge matter disposal to open environment. And no single or specific processes are reported that are found an effective treatment approaches that is associated with their different advantages or limitation. Improvement in recent process technologies and their combined oil recovery approaches with sludge waste disposal can be implemented with resources reuses recommendation and environment protecting regulation. The comprehensive mode of examination of oily sludge waste treatment via BESs can apply for both objectives (such as advanced developments with future research directions) (Hu et al. 2013).

Treatment strategy of petroleum industries produced water (PPW) is done by application of BES unit with application of uplifted cathode electrode potential. It has shown good treatment capability with reduced levels of waste matter (in terms of COD or hydrocarbon removal). And removal of 91% COD and 77% hydrocarbon is found with reduction in TDS levels that is reported during BES operation at appropriate cathode potentials (400 mV). Reduced sulfate concentration is not reported at significant levels due to oxidative reactions that are reported at anode electrode. Enhanced oxidation processes of PPW waste fraction at anode electrode have reported with generation of good power output (negative value of 20.47 mA) with increased fuel cells behavior. Electrochemical mode of analysis (cyclic or linear sweep nature voltammeter) has done with good correlation and good capability of treatment and dynamic microbial cells of the BES unit with loading of real field wastewater has shown dominant nature with effectiveness for petroleum crude oil degradation (Jain et al. 2016).

BESs tools or approaches are applied for wastewater treatment purposes but its organic waste degradation capacity (on BES anode electrode) BES anodes) is found to be poor in nature without directly discharging of electrons or reusing of system. For enhancing the degradation of waste matter performance, BES cathode electrode is applied as additional components treatment for selected or specific contaminant via investigating the number of approaches and these have been grouped into cathode-stimulated treatment (involved electron transfer directly with reduction of contaminants like NO_3^- ion or dye compounds) and cathode-supported treatment (accomplished with toxic contaminant removal occurred by aerobic condition oxidation, algal strain biomass cultivation as well as strong oxidant compounds production for advanced mode of oxidation or membrane mediated treatment). Cathode promoted wastewater treatment process via BES reactions can judge the challenge or problems, with offering good suggestion or recommendations on the future period development of BES designs or operations for best wastewater treatment performances (Jain and He 2018) and shown in Fig. 8.3.

A lot of quantities of wastewaters generation are coming from domestic or industrial resources, posed several challenges (water crisis issue or environmental deterioration) to our healthy environments. Sustainable nature of energy generating, effective wastewater treatment system can provide plausible solution via application of microbial electrochemical technologies with completion of simultaneous treatment of wastewaters. These systems efforts can be big achievement in recovery of clean energy with reclamation of usable water. Various types of configurations, electrode assemblies, and effective designs of MFCs system have been reported for degradation of industrial or domestic origin wastewater via application of indigenous

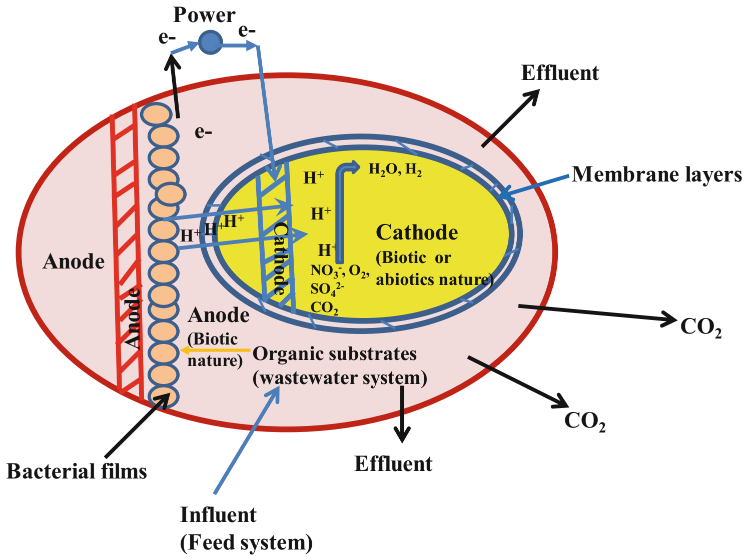

Fig. 8.3 Biochemical system (BES) design utilized for clean energy and energy and electricity power generation via proceeding wastewater treatment (Pant et al. 2012)

or enriched electrogenic microbial systems. Conventional mode of single or dual chambered MFCs system has shown to integrate hybrid MFCs and is applied at scaling up from laboratory level to pilot level with making of various modes of advancements in technical or scientific operation that can be applied for wastewater treatment as well as power generation tasks from few recent years (Rathour et al. 2019) and some waste concentration with its values after bioprocesses treatment is shown in Table 8.1.

8.4.1 Bioelectrochemical Systems (BESs) and Energy Generation

Anaerobic digestion (AD) is normally performed at low temperature and it is shown as attractive technology. At moderate climates (low temperature), this AD is reported for low microbial activity with facilitation of low rates of methane formation. And bioelectrochemical systems (BESs) are reported for enhanced methane production at low temperature via utilization of organic matter in anaerobic digestion (AD) processes. At 10 °C, this methane (CH_4) production is occurred at bioelectrochemical reactor and reported to operate with granular activated carbon as electrodes. Bioelectrochemical systems have been resulted for enhanced CH_4 yield with accelerated rate of CH_4 production as well as increased acetate removal efficiency at 10 °C (Liu et al. 2016).

Table 8.1 Reduced wastes or toxic compounds concentration in bioelectrochemical systems (BESs)

S. No.	Wastes in effluent	Reduced value of wastes in processes	References
1.	Nitrate or dye compounds	Cathode-stimulated treatment reported with reduced contaminants (nitrate or dye compounds) at is operated at mild conditions with microbes involvement	Jain and He (2018)
2.	Toxic or waste organic compounds	A tubular shaped single chambered, continuous MFCs can generate high power outputs having granular graphite matrix (the anode) and a ferricyanide solution (cathode) with reduction of toxic or waste organic compounds	Krieg et al. (2014), Rathour et al. (2019)
3.	Nitrogen and P nutrients in wastewater	Membrane coupled with complete anaerobic treatment of wastewater for renewable fuel (electricity) generation via direct biological conversion of organic matter containing N or P components	McCarty et al. (2011)
4.	Volatile solid (VS) and total solid (TS) reported from two effluents	Mechanical treatment is used in dairy waste treatment with reduction (more than 80%) of the volatile solid (VS) and total solid (TS) reported from two effluents	Lhanafi et al. (2017)
5.	Petroleum produced water (PPW) and petroleum crude oil	Application of BES system under uplifted cathode potential has shown good treatment efficiency with reduced waste concentrations in terms of COD (91%) and hydrocarbon removal (71%)	Jain et al. (2016)
6.	Hydrolyzed product and soluble organic residue with higher COD (3600 mg COD/L)	The biogenic conversion of coal to methane improved from polarization of the electrode. In the bioelectrochemical (BEC) reactor with diluted hydrolysis of product reported with improved methane yield	Song et al. (2016), Piao et al. (2018)
7.	More COD with ammonium nitrogen and phosphate ions	The IPB system helps in removal of more value of (more than 92%) more than 92% COD with ammonium nitrogen (98%) and phosphate (82%). This system has produced a maximum power density (2.2 W/m^3) and algal biomass growth (128 mg/L)	Xiao et al. (2012), Sun et al. (2019)
8.	Higher chemical oxygen demand (COD) with ammonium compounds	Combined process of bioreactor succeeded with removal of chemical oxygen demand (COD ~85%) with	Hu et al. (2017), Lee et al. (2007)

(continued)

Table 8.1 (continued)

S. No.	Wastes in effluent	Reduced value of wastes in processes	References
		ammonium (80%). It has shown resultant effluent concentrations of COD (1591 mg/L) and ammonium (61 mg/L) as more reduced values	
9.	BOD5/COD ratio	Ozonation process enhanced the biodegradability of the anaerobic effluent and is also reported with reduced BOD5/COD ratio (0.15–0.33) from CSTR and IC bioreactors. And SBR has shown more reduced BOD5/COD ratio (0.07) by using biological processes. Sulfate removal efficiency (65%) was also reported from this bioreactor	Hu et al. (2017), Lee et al. (2007)

Highest CH_4 yield (31 mg CH_4. COD/g.VSS) is reported from combined BES-AD process with cathode electrode potentials (−0.9 V-Ag/AgCl) and it can be helped to achieve the 5.3 to 6.6-fold higher or more methane production than AD reactors at temperature of 10 °C. CH_4 (methane) generation rate in integrated BES-AD process at 10 °C has slightly lower value than the AD reactor at 30 °C. External circuit system between the acetic acid oxidizing reaction at bioanode and methane production at cathode electrode is found by utilization of alternative pathways. Electrons from acetate ion to methane are reported during hydrogen production. Methanogenesis from acetate as alternative pathway has helped in higher quantity of methane production rate at low temperature. Combination of BES with AD system is shown as attractive alternative strategy for enhanced performance of AD process in cold areas via performing wastewater treatment (Feng et al. 2017; Liu et al. 2016). In other reports, it has shown enhanced biogenic processes for coal conversion to methane gas and it is reported for bioelectrochemical reactions in anaerobic reactor at polarized electrodes. This electrode (1.0 V polarization) is reported for higher methane yield from coal (52.5 mL/g) lignite. Application of electrode (2.0 V polarization) has minimized the adaptation periods for generation of methane from coal substrates and has slightly less methane yield than 1.0 V value of electrode (Piao et al. 2018).

CH_4 generation from coal resources in the BEC reactor is reported with hydrolysis processes of methane products with soluble organic residues for higher COD value (3600 mg COD/L value). The hydrolyzed product is reported with substrate inhibition effects and can be further inhibited from coal conversion to CH_4. It has reported that diluted hydrolysis product can mitigate the substrate inhibition to methane production. 5.7-fold diluted hydrolyzed product can be inhibited by the methane conversion rate (50%). CH_4 yield (55.3 mL/g lignite) is reported from hydrolyzed product (diluted tenfold) via confirmed anaerobic condition toxicity test.

The biogenic mode of conversion of coal to methane is enhanced from polarization of the electrode in BEC anaerobic reactor with diluted hydrolysis product improved with methane yield (Song et al. 2016; Piao et al. 2018). BES is reported to utilize the MFCs and MECs units and these systems have capability for conversion of biodegradable organic matter into electric energy (Kim et al. 2009).

These systems are found for production of hydrogen bioenergy via application of a microbial cells biofilm on the electrode (biocatalyst). Waste to energy (WTE) technology via MFCs system can be found for treatment of organic contaminant waste coming from domestic or industrial sources wastewater via simultaneous mode production of electric power. From these systems, the maximum power densities (up to 1 kW/m^3) are reported based on reactor volume or size (Rozendal et al. 2008).

8.4.2 Energy from Bioelectrochemical Systems (BESs) with Microbial Fuel Cell (MFC)

Integrated photo-bioelectrochemical (IPB) system has been applied via installing MFCs with algal species containing treatment processes and it has achieved simultaneous removal of organic matter in synthetic solution of MFCs system and also provided nutrients for algal bioreactor. It has shown bioenergy production in form of electric energy with algal biomasses via utilization of BEC and microbiological processes (Kakarla and Min 2019). During the 1 year operation time, EMP system has helped in removal of more value of (more than 92%) COD with ammonium nitrogen (98%) and phosphates (82%). These systems have produced a maximum power density (2.2 W/m^3) and also algal biomass (128 mg/L) (Xiao et al. 2012; Sun et al. 2019). Algal biomass cultivation has produced more dissolved oxygen (DO) value to the cathode reaction side in the MFCs system whereas BES, oxygen reduction is found at MFC cathodes using buffered pH for best medium for algal biomass (known as catholyte). The performance of BES system is affected by illumination periods and DO level. Initial level energy analysis has shown for IPB system that can generate huge quantity of energy in theoretic value via covering its consumption and improved electric power generation. The analysis of the attached or suspended microbial strain at cathode electrode is revealed that diverse nature of bacterial cell texa group of typical aquatic or soil microbial communities. These can achieve the functional roles in contaminant degradation or removal with nutrient cycling (Sun et al. 2019; Kakarla and Min 2019).

Bioelectrochemical systems have shown their application via reduction of energy consumption during wastewater treatment and helping in replacement of energy intensive aeration in waste treatment systems. These systems are also generating electrical energy. Biomass productions in MFCs are reported in range of 10–50%, depending on the microbial cell nature in conventional wastewater treatment with reduction in environmental impact or disposal costs. In this regard, various electrochemically active bacteria have shown their capability for metabolizing biodegradable organic compounds via discharging the electron to an extracellular mode of electron acceptor during bacterial respiration processes. From these bacteria, it has transferred the electron to electrode site via direct mode of electron transfer, electron mediator or shuttles, and electric mode conductive nanowires (NWs) as electron mediator systems (Reguera et al. 2005).

Bacterial electron transport mechanisms have shown better understanding of the biomaterial functions or roles that involved or utilized metabolic pathways for improvement in power generation from MFCs. Biofuel cell systems information can be improved via performing necessary interdisciplinary research works via involving the electrochemistry, microbiology, materials sciences, or surface chemistry with engineering approaches to reactor designs or operation and modeling. From these fields, integration of research systems can generate via increasing the performance or efficient and feasible capacity of BES process for sustainable mode energy generation (Kim 2009; Reguera et al. 2005).

The production of electric power from microbes has been demonstrated with scientific enquiries and electrical power generation is associated with the decomposition of organic compounds. Use of electrochemical devices can be done for harvesting electric energy, coming from the microbial decomposition of organic substrates due to concept of a bioelectrochemical processes. Alternative options for fossil fuels have been intensified with advanced research and significant interest in the scientific community. Driven the prospective application is reported with production of sustainable energy and other synergetic benefits via doing the wastewater treatment and resource recovery. Perspective of production of fuels, electricity, and chemicals is reported by using bioelectrochemical systems (Schirmer et al. 2010).

Production of biofuels and valuable chemicals is found on the basis of working principles of bioelectrochemical systems. Integration of biorefineries with bioelectrochemical systems for the enhanced synthesis of biofuel or other variable chemical production can be shown state-of-the-art thermodynamic feasibility models and methods for evaluating the economic viability of the integrated systems of wastewater treatments (Shemfe et al. 2017; Schirmer et al. 2010).

8.4.3 Energy from Microbial Electrolysis Cells (MEC) and Bioelectrochemical Systems (BESs)

Bio-H_2 synthesis is found from MEC system via performing effective treatment of wastewater and has reported more potential for its application with wastewater generated from industries. These have shown in reduction energy consumption and more economical costs of operation and contained both electrodes and are performed at anaerobic nature. Engineering approach of these systems can be shown effective strategy for microbial fuel cell counterparts, retrofitting into the present or current day status of infrastructure of wastewater treatment. Critical parameters for assessment of MEC system performance are analyzed with assessment of research on MEC function that rhetorically matches the reality. It has shown to generate valuable product (hydrogen) with further testing at plausible level scale under real process conditions (Cotterill et al. 2019).

Application of a MEC system is used for enhancing biogas production at AD reactor with its effect analysis on rate of methane production is reported with utilization of food waste organic matter. AD reactor performance has compared with combined forms of an AD bioreactor integrated with A MEC system (AD +MEC) and these combinations of systems have shown the accelerated CH_4 generation with stabilized and fast organic matter oxidation processes and fast speed of methanogenesis bioprocesses. CH_4 biosynthesis rate with its stabilization periods for AD and MEC bioreactor has reported faster (1.7- and 4-fold) than single AD reactor. At final steady state, the CH_4 yields are found to have same value of the theoretical maximum methane yield. MEC alone cannot increase or enhance the CH_4 yield over theoretic calculation value but it has enhanced the CH_4 biosynthesis and stabilization of BES reactors (Park et al. 2018).

MECs systems are reported to consume the chemical energy from organic matter and it helped in bio-H_2 synthesis. New and hybrid MECs design has shown its improved performance for this fuel generation via achieving the wastewater treatment. This MEC design is reported with externally aligned TiO2 nanotube (TNT) array of photoanodes that is fabricated by anodization of Ti foil and it is supplied for photogeneration of electron current to the MECs mediated external circuit with improved overall performance. The photo-process mediated electron generations have helped in reduction of electron depletion at bioanode. These approaches have improved the proton reduction reactions at the cathode electrode. This 28 mL hybrid MEC operations are performed under stimulated (AM 1.5) illumination (100 mW/cm^2) and shown to exhibit a H_2 evolution rate (1.4×10^3 mmol m^{-3} h^{-1}) a maximum current density (0.371 mA cm^{-2}) and power density (1.4×10^3 mW m^{-2}) and these show 30.8%, 34% or 26% more value than a MEC reactor under dark fermentation condition (Kim et al. 2018).

8.4.4 Bioenergy from Wastewater Treatment via Other Approaches

The bioethanol industry has reported with more demand of water supply and present periods water consumption rate (11–15 dm^3 m^{-3}) in corn grains dry grinded in ethanol production plant is reported for ethanol production in cellulosic ethanol plants capacity (23–38 dm^3 m^{-3}). Feasibility of use of treated wastewater effluent is reported for cellulosic mode or advanced ethanol synthesis with help in making potable freshwater. Two different sources of filtered treated effluent are reported for case study of Bloomington- normal (IL) as sources from resident locations and Decatur IL as mix type waste fractions from industrial and residential nature. It has evaluated and compared the fermentation rate and end product (ethanol) yield from pure form of cellulosic substrates. Analysis for characterization of components has been done for both types of effluent water samples after completion of fermentation processes with ethanol production and reduced quantity of toxic elements. Final ethanol yield (0.36–0.37 g g^{-1} and 0.36 g g^{-1}) reported from Bloomington normal and Decature effluent, respectively, in controlled conditions treatment via applying deionized water. Proper ways of characterization studies under suitable conditions can help in effective treatment of effluent water from production pg cellulosic ethanol in feasible quantity (Ramchandran et al. 2013).

The treatment of wastewater has been achieved with cellulosic ethanol production in biorefinery industries, shown as special challenges. In this regard, a pilot-scale process ethanol production has utilized by using some bioreactors such as CSIR system, an internal circulation (IC) reactor, sequencing batch mode reactor with enhanced ozone oxidation. These have been innovated for effective treatment of biorefinery wastewater which is a challenging task. And very interesting reports have come from CSTR and IC bioreactor application with reduction of COD value in anaerobic treatment. SBR process has shown with nitrogen removal via application of alternating aerobic nitrification and anaerobic denitrification (Lee et al. 2007).

Combined process of bioreactor has been succeeded with removal of 85% of COD value with 80% of NH_4^+ ion. Resultant effluent with COD (of 1.6×10^3 mg/L) and NH_4^+ (61 mg/L) value has reduced values. Further, ozonation process enhancing the biodegradability of the anaerobic effluent is reported with reduced values of BOD5/COD ratio (0.15–0.33) from CSIR and IC bioreactors, respectively. And SBR has shown more reduced BOD5/COD ratio (0.07) by using effective biological process by using a biological process. SO_4^{2-} ion removing efficiency (65%) has reported in using of alternating anaerobic and aerobic processes with final effluent with SO_4^{2-} ions concentration (217 mg/L) (Hu et al. 2017; Lee et al. 2007).

Ethanol concentrations using conventional dry grind procedure have determined for some interval periods (every 2 weeks) for 1 year and these have reported with variations in ethanol concentration with variability pattern for commodity and corn supply. Highest concentrations of ethanol have reported in the month of January due to storage time variation and it has considered for significant factor, affecting ethanol concentrations. It has also shown the effect of various enzymes treatment on mean value of ethanol concentration over a period of year. Two enzymes of liquefaction enzymes have applied at optimal range (pH of 5.8 or 5.1 and two enzymes of saccharification process are used at optimal pH (5). And protease has used in five enzymes treatment for 1-V type treatment. It has reported that the final ethanol concentration (17.5 %v/v) with enzyme treatment V (0.6% more) compared to enzyme treatment 1 has applied for additional amount of ethanol synthesis (600,000 to 100 million gallons/year) in an ethanol plant. More effective enzymes have helped for increased overall dried corn based ethanol plant with more profit value (Ramchandran et al. 2015) and some examples are shown in Table 8.2.

Table 8.2 Energy from wastewater via utilization of bioelectrochemical systems (BESs)

S. No.	Energy	Waste or wastewater treatment	References
1.	CH_4 yields from PW (25.546 ml STP/gVS) and LDP (79.1 ml STP/gVS)	Effluents containing pure whey (PW) and loss of dairy product (LDP) in anaerobic wastewater treatment	Lhanafi et al. (2017)
2.	CH_4 yield (31 mg CH_4.COD/gVSS) 31 mg CH_4-COD/g VSS)	From combined BES-AD system at 10 °C with bioelectrochemical reactor	Liu et al. (2016), Feng et al. (2017)
3.	Methane yield (55.3 mL/g lignite)	From hydrolyzed product (diluted tenfold) with polarization of the electrode in the BEC anaerobic reactor via confirmed toxicity test	Song et al. (2016), Piao et al. (2018)
4.	Methane production rate	1.7 times higher for AD + MEC reactor	Park et al. (2018)
5.	H_2 evolution rate (1.4×10^3 mmol m^{-3} h^{-1}) with a current density (0.37 mA cm^{-2}) and a power density (1.4×10^3 mW m^{-2})	28 mL hybrid MEC operations are performed under simulated AM 1.5 illumination (100 mW cm^{-2})	Kim et al. (2018)
6.	Ethanol concentrations (0.36–0.37 g g^{-1}) and 0.36 g g^{-1})	From Bloomington normal and Decature effluent, respectively, in control conditions treatment using deionized water of ethanol production in cellulosic ethanol plants capacity (23–38 dm^3 m^{-3}) via fermentation processes	Ramchandran et al. (2013)
7.	Ethanol concentration (17.5%v/v)	Two liquefaction enzymes have applied at optimal range (pH 5.8 and 5.1) with saccharification by two enzymes at optimum pH (5). And enzyme protease used in five enzymes treatment (1-V)	Ramchandran et al. (2015).
8.	Production rate (81 ml/L/day) of hydrogen	In a two chambered MRCs used for mixture of VFA in the efficient of a dark fermentation	Rivera et al. (2015)
9.	Maximum hydrogen production (0.53 L/L day), after 3 days	2.5 L MECs with eight separate electrode pairs (graphite fiber brush anodes pre-acclimated) for current generation using acetate compound with 304 stainless steel mesh cathodes (64 m^2/m^3)	Rader and Logan (2010)
10	Increase of 12% in biogas production over the control (1353 mL CH_4 day^{-1} at an injection flow rate of 1938 mL H_2 day^{-1})	Hydrogen pulse addition on digestion performance of sewage sludge reported with increase in efficiency of methane production in theoretical process of coupling bioelectrochemical systems (BES) along with H_2 biosynthesis and subsequent AD process	Martinez et al. (2019)

8.5 Conclusions

Wastewater generation in huge quantity is reported from various sources such as municipal, domestic, or institutional places with food processing, agricultural, or industrial industries. Lot of money is reported to consume for its efficient treatments. Many toxic or useful waste sources in form of organic compounds or elements are present in wastewater effluents and it has posed many environmental issues with big challenges. It needed to apply effective treatment for biodegradable compounds before disposal to open into open environment. Currently many effective treatments (i.e., bioelectrochemical system ~BES) are employed for treatment of different types of wastes in water or other industrial effluent via generation of electric power or other biofuel generation (hydrogen, methane, and ethanol). BES is reported to utilize the MFCs or MECs for generation of different types of bioenergy with reduction in toxic compounds or useful nutrients. BOD and COD value in polluted water bodies is reported to reduce with generation of sustainable energy. Sometimes some saccharfication enzymes are used for hydrolysis of complex waste residues (cellulose) during ethanol production.

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