Potential Role of Beneficial Microbes for Sustainable Treatment of Sewage Sludge and Wastewater

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1 Introduction

Intensification in the industrial activities and accelerated development in the urban and semi-urban areas is generating high levels of organic, and inorganic contaminants that are specifically discharged to the wastewater and sewage networks (Atashgahi et al. 2015). Sewage sludge not only contains different levels of contaminants but also different bacterial communities. This microbial community may vary depending on treatment conditions, industrial activities, and sewage origin but these microbial communities have significant potential to treat the sewage sludge for safe use for arable land, agricultural production, horticultural uses, and industrial uses by extracting valuable products. But sustainability of use is greatly dependent

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V. D. Rajput et al. (eds.), *Sustainable Management and Utilization of Sewage Sludge*, https://doi.org/10.1007/978-3-030-85226-9_4

on system efficiencies, implementation of policies, and cost associated with technological processes (Shchegolkova et al. 2018).

In the twenty-first century, the sewage sludges generation and their disposal are considered as greatest challenges for environmental protection, changing climate, human safety, ecosystem functioning, biodiversity, and national and international economies. Water is a must for the existence of life, from maintenance and operation of households to extensive agricultural and industrial use. It is our ethical, ecological and political responsibility to critically think about management of natural resources. Due to shortage now it is vital to safeguard the good quality water as there is a significant loss of its share below the surface and in the landscaping, water channels. Industrial, and domestic effluent is an environmental concern even if it is going through a sewerage system and treated in the urban wastewater treatment plants and eventually released openly to environment.

A sizeable quantity of refused water is generated by domestic community companies, urban local builds, and industries, that water without suitable handling discharged into neighbouring water bodies, lakes, and rivers, cause water pollution. This mess-up handling of wastewater causes many challenges such as lack of energy for the treatment of discarded water as well as deficiency of freshwater. The overall challenge is to plan such schemes which are not only important treat wastewater but also helpful in the generation of many energy compelled products. Therefore, this chapter is focused to highlight the significance of microorganisms and microbial techniques for the sustainable, efficient, and cost-effective management of wastewater and sewage sludge.

2 Role of Microorganisms for Sustainable Management of Sewage Sludge and Wastewater

Biological treatments aim to decompose toxic organic compounds (pharmaceutical compounds, xenobiotics, and petroleum derivatives) and decrease pathogens' population, lessen the effects on environment and human beings. Among biological processes in wastewater treatment plants (WWTPs), activated sludge (AS) processes are widely used across the world and for removal of pollutants and they are being used for more than a century, due to their biomass retention capabilities, high toxin degradation, and nutrient removal efficiencies (Xia et al. 2018).

The AS procedures have been studied extensively and the recent results have revealed that full-scale system of AS offers a core microbiome and its activities offers good decontamination of wastewater. By-product of sewage sludge usually have greater microbial diversities, and it may vary depending on origin of sewage, industrial activity, treatment conditions (e.g., redox conditions, and liming). The processes of activated sludge depend on the capability of microorganisms for the utilization of organic material as basis of carbon and/or source of energy and other essential minerals for growing processes, and plays crucial roles in the biodegradation of organic materials, removal of specific nutrients such as ammonia, sulfate, phosphate, and nitrate and conversion of hazardous compounds to less toxic products (Rahimi et al. 2020).

Biological processes and treatments are dependent on nematodes, bacteria, and other soil organisms that causes decomposition of organic wastes by utilizing normal and specific cellular processes. Typically, wastewater and sewage sludge have high amount of organic matters, like partially digested foods, garbage, and waste. Moreover, it also contains numerous pathogenic organisms, toxins, and heavy metals. The major purpose of biological wastewater treatment is creation of a system that can easily collect the end results of decomposition for further disposal activities.

These microorganisms cause decomposition of organic pollutants to get food and energy. They may stick together during this whole process and causes the creation of flocculation effects that in turn allows the settlement of organic matter and organic residues in the solution. In this way it is essentially helpful for the safe and easy management of sewage sludge because it can be dewatered with great ease and can be disposed of as solid waste. Therefore, the role of microorganisms for the treatment of sewage sludge and wastewater is greatly helpful to achieve food security and environmental sustainability. Microorganisms may not cause the complete mineralization of all toxic compounds but causes a significant conversion of more toxic products to the less toxic ones and thus protects environment, plants, animals, and humans from the risks associated with contamination.

2.1 Composition and Structure of Bacterial Communities and Their Control

Relative abundance, occurrence and activities of several microbial communities in sewage sludge greatly affects the stable practices and operations of biological based wastewater treatment plants (WWTPs).

Although there is always a significant variation in the community composition of microbes, but this variation is associated with alterations in functional capabilities and structural dimensions of microbial communities. Functional stabilities in the microbial communities have been recognized as major factors that affects the efficiency of wastewater treatment (Wang et al. 2014). Microbial diversity and changes in the community structures greatly affects the functional stability and performance of WWTPs. While, there are many factors that causes modulation of community structures of microbes in WWTPs. Usually this variation is based on the presence of different types of bacterial niches such as autotrophs, heterotrophs, and chemotrophs, and the sources of effluents.

Since the past decade, there have been intensive studies to check the functional stabilities and other properties in the activated sludge in WWTPs. These studies are especially focused on dealing with sewage sludge and wastewater in the WWTPs. Communities that are directly involved for biological treatment of dangerous substances such as from industrial waste harbours different populations of microbes which are specifically adapted to numerous stresses in these systems. Effluents from textile industries also contains higher levels of dyeing additives, dyes, and varying degree of other chemicals. Some of these contaminants are non-biodegradable, mutagenic, toxic, and carcinogenic and therefore can pose major threats to environment and health.

Generally, textile wastewaters have low ratio of biological oxygen demand/ chemical oxygen demand (BOD/COD) that is around 20%. Moreover, there is a varied range of pH (4–12) and therefore it may include numerous inhibitor composites that can exert hampering effects on biological treatment of wastewater, adsorbable organic halogens, active substances (e.g., chlorine compounds) (AOX) and higher concentrations of salts. This entirely makes it difficult to treat textile wastewater and thus greater care and management is required to achieve sustainability. Furthermore, microbial communities in the wastewater are different than the communities present in the industrial wastewater and requires different kinds of handling techniques and management approaches.

Studies have shown that in the municipal (domestic sewage), predominnat species was Proteobacteria phylum (21–65%) that belongs to Betaproteobacteria that represents a specific class of microorganisms responsible for degradation of organic matter and cycling of nutrients. This sewage also contained other less dominant taxa such as Bacteroidetes, Chloroflexi and Acidobacteria. Whereas, proteobacteria were found to be abundant in the sewage generated by the industrial activities. This sludge was reported to contain a higher level of obstinate compounds coming from petroleum refineries, pharmaceutical industries, factories for animal feeds, textiles, and others.

Conditions of biological treatments are other modulating factors and studies have reported that microorganisms were abundantly found in the anaerobic-aerobic and anaerobic systems as compared to the aerobic systems. While the abundance of proteobacteria was reported to be more in the aerobic environment. Whereas the abundance of Bacteroidetes was reported to be more in the bioreactors provided with anaerobic conditions. Furthermore, there are some chemical attributes such as concentrations of micronutrients, pH presence of different types of toxic compounds such as heavy metals, and other inorganic, and organic pollutants and oxidation and reduction conditions in the biological treatments can directly affect structure of bacterial communities in the sludge.

Like in Brazil, the sulfur oxidoreductive bacterial community was composed of 22 different families, and could have been clustered by the chemical characteristics, such as S, Zn, K, N, Mn, and P and sewage sources (Meyer et al. 2016). Studies have also reported that temperature also impacts the diversity of microbial communities and their structures in WWT plants. Temperature is most important among the physical factors as it is key players for the determination of survival rates of microbial communities. Moreover, it greatly controls the composition of hydrocarbons and therefore due attention should be given to this factor for effective and efficient management.

Biological enzymes always have good participation for the degradation pathways but require optimal temperature for their functioning. Every little or major change in the temperature will directly affect the metabolic turnover and thus management situation may fluctuate. Moreover, temperature specification is also important for the breakdown processes of different compounds. Increased temperature is always associated with the increased rate of microbial activities and maximum activities can be sustained at the optimal temperatures. These activities are declined with further decrease or increase in the temperature and are eventually stopped after reaching a maximum limit. Scientific studies have also reported that cold temperature produces effects on the growth of microbes by decreasing the availability of water, changing the energetics, reducing the molecular motion, and increasing the concentration of solutes due to reduced water availability. It also has been reported that adaptation of different communities of microbes to lower temperatures is a problematic scenario for WWT systems.

Likewise, pH of specific compound that is either basic, acidic or alkaline in nature of the compound, exerts its own effects on metabolic activities of microbes and may also affect the efficiency of removal process. Low or high pH values also causes negative results on microbial communities and their metabolic processes because these creatures are greatly intolerant to even little fluctuation in pH. Similarly, microbial communities and their activities are also dependent on the concentration of oxygen because some species requires oxygen and some do not requires oxygen for their survival and bio-degradation processes. While, bio-degradation can be carried in both anaerobic and aerobic conditions because oxygen is an essential requirement for various living creatures and some that does not requires oxygen may have developed slight tolerance. Studies have reported that the metabolism of hydrocarbons is greatly improved due to presence of oxygen.

The balance for essential nutrients is also important for growth, survival, and reproduction related activities of microbes. An optimal balance is not only important for these processes but is also required to accelerate the efficiency and rates of biodegradation. Nutrient balancing is especially important for P and N as they can improve the efficiencies of biodegradation by optimization of C:N:P ratios in the sewage sludge, wastewater, and soil systems. Microorganisms also needs different nutrients such as P, N, and C for their growth, development, survival, and functioning. Addition of appropriate quantity of these nutrients is important strategy to improve their metabolic activity and functioning and thus the process of biodegradation can be greatly accelerated in the colder regions. The process of biodegradation is especially limited in the aquatic environments due to limitation of nutrients. The microbes that feed on oil also needs nutrients for their growth, and development. Usually, these nutrients are available in their surroundings and in the natural sources but their concentration is low so they must be augmented by some external sources for better functioning and activities of these microbes.

Biotic factors also exert direct influences on the degradation of different organic compounds due to the competition between numerous species of microorganisms for limited sources of carbon and predation of microbes by bacteriophages and protozoa, or due to antagonistic interactions between numerous microorganisms. The degradation rates of contaminants is also dependent on the levels, concentrations, and types of contaminants, and the amount of catalyst for the specific degradation reactions. In this specific context amount of catalyst present indicates the specific number of organisms that can metabolize different contaminants. Moreover, the production of enzymes by the cells is also important factor that affects the overall degradation and stabilization of contaminants. The specific expression of enzymes by the reduced or improved rate of contaminants degradation also have significant importance to predict and measure the enzymatic activities and degradation of pollutants. The major biological factors in this context are size of bacterial population, community composition, gene transfer, interaction of different microbial and other communities, enzymatic activities and mutation.

Despite of the significant progress for the effective management of sewage sludge and waster water by microbial processes there are some kinds of associated shortcomings. Scientific data is also indicating that issues related to structures of microbial communities can be managed in the WWTPs but it only involves and manages smaller populations and samples. Other than this majority of designs and scientific knowledge is only being applied to pilot systems and bioreactors in the laboratories (Saia et al. 2016). Controlled operational conditions such as flow of effluents, aeration, and temperature can easily affect the diversity of microbial communities (Muszyński and Załęska-Radziwiłł 2015; Muszyński et al. 2013). Whereas most of the scientific studies are based on using conventional techniques and therefore only 60–90% of populations of microbes have been cultured. Emerging molecular, biotechnological, and bioinformatics techniques should be implied for better understanding about community structures and their functioning. Therefore, the tolerance, survival, and working capabilities of these microbes can also be improved by using latest technological solutions. Furthermore, ecological role of microbial communities can also be significantly improved, and thus environmental protection can be attained on sustainable basis.

2.2 Microbial Activities

In the different spatial and temporal conditions, effluent treatment plants (ETPs) may contain different level of microbial communities as dynamic associations. The various co-existing populations of microbes in wastewaters vary with the operational conditions of reactor. Their involvement for overall degradation of pollutants may cause unprecedented controls for bioremediation of contaminants and effluents (Manefield et al. 2005).

Microbes perform sewage sludge and wastewater treatment either through aerobic digestion or anaerobic digestion.

1. Aerobic, in these microorganisms need oxygen for decomposition of organic matter to microbial biomass and carbon dioxide.
2. Anaerobic, in these microbes do not require oxygen for decomposition of organic matter, and often produces excess biomass, carbon dioxide, and methane.

Anaerobic digestion is an auspicious biotechnology for highly polluted wastewater with organic contaminants and hence contains higher amount of substances that can be degraded biologically. The substrate digestion in anaerobic reactors causes significant lessening in the total contents of volatile solids and additionally the weight and volume of the substrate. The process of anaerobic digestion is complex and consists of several biochemical based processes and are systemically mediate by the interconnected communities of microbes from Archaea and bacterial domains and some smaller percentages of viruses and eukaryotes. These biochemical based transformations offer significant degradation of complex organic compounds to the reduced and oxidized forms of carbon such as methane, and carbon dioxide (Batstone and Virdis 2014).

Anaerobic digestion process comprises of four steps such as hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Hydrolysis causes the cleavage of the complex biopolymers by the action of extracellular enzymes of specific fermentation causing bacteria to smaller monomers like proteins, lipids, soluble organic matter, and polysaccharides, these are all degraded and the final products are further treated through acidogenesis to produce volatile fatty acids (VFAs). During acidogenesis, monomers are converted by fermentative bacteria mainly into volatile fatty acids like alcohols, propionic acids, butyric acids, acetic acids and lactic acid, and also molecular hydrogen.

Mostly, these bacteria belong to the category of obligate anaerobes but sometimes facultative anaerobes may also be there. During the process of acidogenesis, volatile fatty acids are converted into molecular hydrogen, CO_2 and acetate. Acetogenic bacteria anaerobically oxidized the hydrolysis products other than acetate such as H_2 and CO_2, i.e., propionate, alcohols, aromatic acids, longer-chain fatty acids and aromatic acids into acetate. During the process of methanogenesis, methane gas is produced by three main ways, methylotrophic, acetolactic, and hydrogenotrophic by methanogenic archaea.

Aerobic respiration is though most effective way to decompose organic matter and waste material but may not cause complete breakdown of effluents. Porous solid materials are present in the tanks, where biofilms can be easily developed, thus enhancing the numbers of microorganisms and thus the efficacy of decomposition process. The produced material is solid in nature and is known as activated sludge is formed during this process, containing a mixture of undigested materials and microbes. Since all of vital microbes are present in it to break down incoming waste, some of it is also added to new batches of sewage. Mostly the addition of aerobic bacteria is for the new treatment plants in the aerated environment. Free oxygen is used by this bacterium within the water for degradation of contaminants in the wastewater and then convert it into energy to be used for growth, development, and reproduction.

3 Strategies to Using Microbial Techniques for Wastewater Treatment

Global reports of subsurface heavy metal pollution of water have become a major health problem and, in this regard, proper knowledge of the source of wastewater and its biological, physical, and chemical aspects are important. It is very important to identify the appropriate strategies for treatment. Microorganisms are partly the key to reducing pollution and maintaining the stability of biological systems. The implementation of biological wastewater treatment technology has many advantages as opposed to other treatment measures, relatively inexpensive costs, minimal emissions, and less detrimental effects on the environment. Also, biological wastewater treatment technology is reaping economic benefits against both chemical as well as physical therapy technologies, in terms of rehabilitation costs and investment of capital (Mittal et al. 2011).

3.1 Biological Treatment Techniques

In Aerobic treatment, the pond contains bacteria and algae that can survive in the aerobic state. Cao and Li (2011) proposed electrolysis involving the biological oxidation procedure for wastewater which contains alkyl-benzene sulfonate. Souza et al. (2011) used bio-activated carbon to treat refinery wastewater for reuse. These bio-compounds can bear a wide range of pH and temperature. Furthermore, they are more suitable in environmental and Petrochemical implementation than synthetically made surfactants because of naturally producing macromolecules like fatty acids, lipoproteins, and glycolipids.

In the Anaerobic technique, the pond is involved in the fermentation procedure which is especially effective in eliminating organic compounds from the solution and eliminating high concentrations of BOD and COD. The anaerobic treatment system has been working in wastewater of industry treatment for several years. In this process, biogas produced that containing methane as well as carbon dioxide. This process can take place in places where organic matter is available but redox potential is lower. Both aerobic and anaerobic processes can be employed in the treatment of dirty water (Table 1).

Table 1 Comparison among aerobic and anaerobic systems

Factors	Aerobic	Anaerobic
Temperature	Low	High
Nutrient necessity	High	Low
Effluent quality	High	Medium
Odor	Low potential	High potential
Energy demand	High	Moderate

3.2 Microalgae Role in Treatment of Wastewater

Microalgae contain photosynthetic ability that change solar energy into biomass and have the efficacy to absorb important nutrients like N, P in a short time. The microalgae involve in the treatment of sewage systems in a wide range and are called tertiary treatment procedures that can extract organic ions. Extract of organic ion get by biologically or chemically (Abdel-Raouf et al. 2012).

3.3 Microbial Electro Remediation Technique

Major portion of metal wastewater produced by humans and industries. The metal-laden polluted water causes critical environmental and health issues and should be properly managed to avoid negative consequences. A significant volume of metal-loaded wastewater is produced due to industrial and human activities, for removal of metal ions strict instructions have been clasped to avoid contamination. An ideal approach is not only to remove metals but collecting and retrieving them during the treatment procedure. Although there are numerous ways to treat or remove arsenic from water and wastewater, recent research has led to the development of technological approaches that seem economically realistic, low cost, and friendly for the environment.

Therefore, there is an urgent need for serious research and development in this direction so that modern techniques can be further advanced, and its scope of application can be extended to the real situation in the direction of pollution prevention. Traditional techniques such as precipitation, coagulation, and the removal of metals are needed to find a solution, which is generally considered less effective. It is costly to treat methods of activated carbon-based absorption, ion exchange, and membrane technologies that involve large amounts of industrial pollutants and wastewater that contain large amounts of heavy metal ions that cannot be operated on a large scale.

3.4 Microbial Treatment of Sewage Sludge Concerning Specific Organic and Inorganic Contaminants

Sewage sludge is a semi-solid material and remaining of municipal and industrial wastewater. The word "septage" is also known as the simple treatment of sewage, but it is involved in a clean system from the site, like as a septic-tank. The treatment of sewage sludge describes various methods that are used to dispose and manage that sewage sludge produced during the treatment of sewage. That sewage is usually with more amount of water with lower quantity of solid materials. In Primary sludge, settleable solids are eliminated during primary treatment. While in secondary sludge the secondary clarifiers include in treated sewage sludge from bioreactors of secondary treatment.

3.5 Treatment Processes for Organic Contaminants

The sewage sludges are treated by using various types of techniques, its objective is to lessen the organic matter amount and various harmful microorganisms which cause diseases inside solids. Most techniques include aerobic and anaerobic systems. Sludge technique about 50% and also provide biogas which is a good source of energy (Cao and Li 2011).

3.6 Anaerobic Technique

Anaerobic is a bacterial procedure when oxygen is not present. This procedure includes a thermophilic technique where the sludge is fermented at 55 °C temperature inside the tank or 36 °C in a mesophilic system. MAD (Mesophilic anaerobic digestion) is also an easy method for the treatment of sewage sludge. In this method, the sludge is fed into big tanks and retain for a minimum of 12 days which allow digestion procedure to digest sludge. These are including acidogenesis, hydrolysis, methanogenesis, and acetogenesis.

In that procedure, the complex sugars and proteins splits into various compounds like methane, carbon dioxide, and water (Souza et al. 2011). Anaerobic produces biogas with a major amount of methane which is used to run engines and provide heat to the tank. Methane production is the best advantage in this process. While in liquid sewage sludge the denitrifying bacteria convert nitrate to dinitrogen which removes that nitrate from sludge. The solid sewage in primary treatment separated is anaerobically fermented by bacteria.

3.7 Aerobic Technique

This process occurs when oxygen is present that directly involved in the continuation of the procedure of activated sludge. In this technique, the bacteria digest organic matter and release carbon dioxide. In absence of organic matter, the bacteria starting die and other bacteria used them as food. This process stage is called *endogenous respiration*. Then reduction of Solids occurs in this stage. Because aerobic technique happens faster as compared to anaerobic and the aerobic capital cost is also lower. Aerobic technique can also be obtained by using jet aerators that oxidize sludge. Excellent bubble spread is usually a more cost-effective method of dispersal but plugging is usually a problem due to sedimentation in small air holes. Coarse bubble spread is commonly used in tanks of activated sludge or the flocculation.

3.8 Treatment Processes for Inorganic Contaminants

Inorganic contaminants from wastewater are removed by Bio-absorption and Bioaccumulation. Bio-absorption is a fast and reversible passive adsorption mechanism. The inorganic contaminants like metals are retained by physiochemical interactions like (adsorption, ion exchange, precipitation, crystallization, and complexation) between the metals and functional groups of cell surface (Fosso-Kankeu and Mulaba-Bafubiandi 2014). Several factors affects bio-absorption of contaminants like pH, biomass concentration, ionic strength, particle size, temperature, and other ions present in solution.

While bioaccumulation includes both extracellular and intracellular processes. In general, bio-absorption is inexpensive as biomass can be produced from industrial waste and offers significant benefit of regeneration. On the other hand, bioaccumulation is expensive because the processes occur in living cells whose reuse is limited. Bacteria also causes elimination of heavy metals from wastewater through functional groups present in their cell wall-like aldehydes, ketones, and carboxyl groups and thus produce less chemical sludge. Brown and red algae are also being used as bio-absorbents, and the use of yeasts and fungi has also been reported for absorption.

3.9 Microbial Ecology of Sewage Sludge and Wastewater Treatment

Biological treatment of wastewater and sewage sludge is most important biotechnology implementations as the driver of the critical systems microorganisms are key to its success. So, the study of dirty water microorganisms is of clear importance. However, the significance of treated wastewater reactors is overlooked as a model system for the environment of microbes. No doubt, the microbial environment of bioprocesses is of great importance for the performing bioprocesses, especially in WWT (wastewater treatment).

Microorganisms have their characteristics during the treatment of wastewater, and they focus on the procedure that is used. There are several types of therapies, including biases, anaerobic therapies, and aerobic procedures that involve protozoa and bacteria, but their fate is unnecessary. The condition of the fungus has a endurance rate such as low pH and low nitrogen which makes the fungus well-thought-out wastewater treatment. Thus, the fungus has the potential to impair the ability to settle sludge due to its fibrous structure, which can affect this process. The rotifer presence at the beginning of treatment of wastewater is the best sign as it can absorb dispersed organic matter and bacteria (Pagnanelli et al. 2009).

3.10 Ponds Stabilization

Waste consolidation ponds are an unconventional system for treating wastewater. This stabilization of wastewater, known as biological treatment, that can work well when equipment maintenance is limited, and directly promotes better thickening of sludge. The proper architecture will help in the cultivation of algae and bacteria which will effectively and completely remove the organic waste in the water thus reducing the problem during the treatment and wastewater disposal (Vaajasaari and Joutti 2006).

3.11 Structural Units of Bacteria

Heterotrophic bacteria have a significant role in organic matter removal from wastewater treatment. That bacteria work in the treatment of wastewater in clusters such as biofilm or granule and floc.

3.12 Flocs

Floc is sludge that forms a bacterial colony by attaching to cells and pollutes wastewater through physiological chemical processes. Flocs contain bacteria and EPS. The content of microorganisms and factors mediates flux stability because environmental stress causes the floc to disintegrate.

4 Wastewater as an Exceptional Resource of Renewable Energy

Wastewater which is produced from different sources is enriched with many different nutrients, minerals, organic matter different metabolites which are used for the progress of many microorganisms, algae, and various plants that are used to generate renewable energy products. Methane gas is released when organic stuff was decomposed in an oxygen-free atmosphere (Koch et al. 2015). When the solid slush is treated via thermal hydrolysis, a large quantity of methane gas can make. Then waste is entered into an anaerobic digester, starts breakdown, and obtains the final product in the form of methane gas which utilize as natural gas (Maragkaki et al. 2017). A distinctive wastewater has a 0.5 kg/m^3 COD value and tentatively can produce 1.47 to 107 J/kg which oxidized to CO_2 and water while energy density of wastewater is 0.74 to 107 J/m^3.

5 Strategies for Energy Adoption from Wastewater

Processing to their capability as energy basis procedure streams must be distinguished by succeeding input, intermediate and output streams that acceptable to technical possibilities for recovering energy from wastewater.

5.1 Inputs

Organic content of carbonaceous dissolved and suspended that was in wastewater ways its energy potential as a chemical nature. The absorbance of carbon dioxide through sunlight energy and usage of wastewater for growth media is due to their inorganic components (Bhatia et al. 2019).

5.2 Intermediates

Many intermediate compounds were prepared by green plants, algae, and microorganisms which are used as a storehouse of biochemical energy. For their activities, these compounds are not only used by microorganisms but also by animals to meet the necessity of energy. These compounds can also be used to produce various energy products for example gaseous methane or hydrogen, biodiesel, or liquid ethanol, or solid dry biomass by the use of specific microorganisms (Evcan and Tari 2015).

5.3 Outputs

Particularly fuel provided by methane can be utilized to generate electricity, heat, and even in propulsion automobiles. The presently provided system is the least effective and it can transform 25–35% of thermal energy to electrical energy and it causes energy losses (Kassongo and Togo 2011; Naina Mohamed et al. 2020). To make it better and efficient joined heat and power solicitation is suggested also skills that transformation of inputs towards intermediates with the assistance of carbon-bound energy into biodiesel, biogas and finally convert into outputs with the help of gasification. Further, it changes the inputs directly into outputs by heat and microbial fuel cells for generation of electricity (Ungureanu et al. 2020).

6 Beneficial Energy Products Generation from Wastewater

If wastewater treatment is controlled, it can produce many valuable stuffs. To obtain valuable material from wastewater biological wastewater system is commonly used. Varieties of products that can be specifically utilized in the form of biofuels are produced from wastewater skills, which are described in Table 2.

Table 2 Energy products recycled from various sources of wastewater, their operational feature and characteristics

Bioenergy produced	Source of wastewater	Operational conditions	References
Biogas	Sewage Sludge Waste from municipal source	Use of anode and neutral red graphite and modified bacteria Dynamic Membrane Filter By using anode reactor pH range: 6.8–7.3	Rahimnejad et al. (2015) Quek et al. (2017) Xu et al. (2018)
Biodiesel	Diary Wastewater Sludge Textile Wastewater Domestic Wastewater	Sludge dewatering and drying Bioremediation of Microalgal followed by lipid and biodiesel production Cultivation of Microalgae Nostoc sp., Chlorella sp.	Leandro et al. (2019) Fazal et al. (2018) Mostafa et al. (2012)
Microbial Fuel Cell	Urban Wastewater Sewage Sludge Starch Processing Wastewater	Presence of salt bridge, two-chamber of graphite electrode Microbial fuel cell: brush electrode, graphite fiber brush electrodes Carbon paper anode	Slate et al. (2019) Liang et al. (2011) Lv et al. (2014), Malaeb et al. (2013)

7 Mechanisms Involved for Recovering the Renewable Energy Products

To produce a specific type of energy stuffs many values added energy objects from wastewater are digested with the help of many microorganisms. The components which are left after digestion are further treated with the help of many physical as well as chemical methods to get more energy. A huge variety of energy products also be taken from wastewater sewerages (Khalid et al. 2011). Methods that are used to produce energy from wastewater are described below:

7.1 Production of Biogas

Anaerobic handling of wastewater treatment offers the capacity to speedily remove organic contents of waste while decreasing the energy usage of dealing method and the manufacture of sludge and microbial biomass (Cavinato et al. 2011). It is a difficult procedure that includes various reactions in the absence of oxygen like methanogenesis, acetogenesis, and hydrolysis (Bhatia et al. 2020a, b). On a vast variety of waste discharges anaerobic digestion is very useful effluents like sewage sludge, industrial wastewater, domestic wastewater, it is also beneficial for the alteration of useful products into different forms such as biohydrogen and methane (Parihar and Upadhyay 2016).

Formation of slush in wastewater generate by-product which takes more dealing. The decrease in sludge and energy utilization are the two points that make it economically striking for industrial and municipal waste streams to reflect direct anaerobic pre-treatment of wastewater. This digestion is exaggerated by many reasons like temperature (25–350C), pH (~7), C/N ratio, carbon sources, moisture, and nitrogen. Just because of fewer disposals AD of manure sludge is treating plants and is eco-friendly also. Significant degradable organic components are also produced by direct anaerobic treatment (Manyuchi et al. 2018). Effluents that are produced by anaerobic treatment are not directly throwing into receiving water and they require aerobic polishing. The average ambient temperature of the wastewater influences anaerobic dealing design quality. Effective anaerobic treatment of wastewater as low as 150C is achievable but the use of anaerobic digestion is not reserved in contemplation below 120C (Bhatia et al. 2017).

7.2 Microbial Fuel Cells

Bacterial oxidation process involved in microbial use cell in which bacteria oxidized organic matter to treat the wastewater and play a role in cation exchange process of cathode and anode in which electron transfer through electricity production due to difference in potential coupled with flow of electrons (Rahimnejad et al. 2015). Microbial fuel cells are the advanced and emerging technology that has been successfully operated in pure as well as in mixed cultures and enriched by activated sludge from wastewater treatment plants (Forss et al. 2017). This technology is eco-friendly due to the already presence of bacteria in wastewater to produce electricity as a catalyst. Despite this advantage, its advancement is hindered due to low power and high cost and valuable products.

Waste activated sludge (WAS) present a major ongoing disposal challenge and by-product of activated sludge-based water treatment for water management authorities worldwide. Conventional waste-activated sludge has been used in agricultural practices such as preparation of land, soil health, offensive odors, and disease risks from toxic chemicals and pathogens. These restricted chemicals hinder the acceptance in public for this adaptation (Egan 2013). Sustainable waste-activated sludge consists of the recovery and reuse of value-added products and also has the potential to minimize environmental as well as human harmful impact. This implementation is usually have been applied in the agriculture sector due to high nutrient and organic matter. It is also a rich source of making of methane gas by anaerobic digestion when mixed in primary sludge.

The land application and implementation of urban wastewater is necessary as compared to rural wastewater is necessary because of the accumulation of industrial effluents which results in too much contamination in the environment as well as in human health which is harmful to the food chain and animal health (Campbell 2000). The production of electricity by thermal energy is also a popular and sustainable way for WAS management (Rulkens 2007). However, it is a cost-effective procedure as additional fuel is required to maintain additional facilities and requirements due to higher energy utilization due to high moisture contents and lower heating values of biosolids (Wang et al. 2008). There is a fundamental challenge for specific biorefinery approaches due to presence of all compound of WAS system in the heterogenous and single complex mixtures.

7.3 Amino Acids and Proteins

Waste activated sludge can be collected as a source of protein and amino acid which consist of organic compounds in the type of protein, lipids, and polysaccharides. It contains almost 70–80% protein fraction in which 50% dry weight of bacterial cell is present (Raunkjaer et al. 1994). Consequently, protein derived from waste activated sludge present an impactful and potential source which is the main source for production of feed of animals compared with traditional source of protein. However, detoxification of sludge is carried out for removal of heavy metals, sterilization process (Adebayo et al. 2004).

The solubilization of intracellular material is an effective way for recovering protein from waste-activated sludge. Thermal digestion is one of the easiest methods which are supported by the centrifugal separation. This process increases the wastewater sludge decomposing ability and break down of decomposing sludge and lysing of the microbial cell. Thermal digestion has a notable profit such as low-cost treatment, no use of additional waste, no use of reagents for waste degradation, use of effective heat exchange. The efficiency of chemical and mechanical treatment on protein extraction is described in two activated sludge and check the compatibility with quantification method (Ras et al. 2008).

The efficacy can be improved by applying mechanical and chemical treatments and various extraction protocols and similar approaches. Triton treatment is used to extract the protein and show the significant hydrophobic interactions linking protein with extracellular polymer matrix. The waste activated sludge amino acid is friendly for the environment due to associated amphiphilic molecular structure which contains carboxyl groups and amino acids. The use of amino acids as powerful inhibitors to regulate destructive responses in a few unique metals in acidic media has been confirmed by a progression of examinations (Khaled 2010).

7.4 Bio-Pesticides

Nitrogen, Carbon and phosphorus is the enriched nutrient source from waste activated sludge which is the potential and feasible medium of growth for microbial accumulation to produce valuable metabolic products. *B. thuringiensis* (Bt) can produce the proteinaceous Para poral crystal inclusion during spore formation which is called endotoxin which is the most famous bio-pesticide globally (Bravo et al. 2001). The production of these bacteria depends on the growth medium of nutrients sources like nitrogen, carbon, protein, and yeast sources (Lisansky et al. 1993). Reuse of waste-activated sludge as a medium for Bt production depends upon its utilization in agriculture for pest control and economical as well as compatible exercises. Three possible strategies are important for Bt production process as Fermentation, recovery, and formulation of products. Several factors like pH, dissolved oxygen concentration, C/N ratio, foaming, and inoculum sludge which have an impact on the production of bio-pesticide.

7.5 Bio-Flocculants and Bio-Surfactants

Bio-surfactants and bio-flocculants are the significant metabolic products during microbial transformation. Microorganisms secreted polysaccharides, cellulose derivatives, and lipids which are consumed in mineral and chemical industries such as food and wastewater treatments (Flores et al. 1997; Jegou et al. 2001). Bio-flocculating activities are non-toxic and degradable for humans and the environment as compared with synthetic flocculants (Yokoi et al. 1996). Due to the high cost of these by-products, the use of this treatment is limited due to its association with the supplies of organic sucrose and glucose. Waste activated sludge is one of the best reservoir for separation of bio-flocculant producing microorganisms during aerobic process occur naturally. Moreover, a variety of different bacterial strains of bio-flocculants have been isolated from waste activated sludge named as *Bacillus cereus*, *Achromobacter* sp., *Agrobacterium* sp., *Enterobacter* sp., *Pichia membranifaciens*, *Exiguobacterium acetylicum*, *Rhodococcus erythropolis*, *Solibacillus silverstris*, *Saccharomycete* spp. etc. (Wang et al. 2014).

8 Microbial Fuel Cells for Improved Bioremediation

Microbial fuel cells (MFCs) can be used as power resource and as a tool for bioremediation. By creating an electrical connection between the anaerobic sediments and aerobic water column, an MFC can increase the metabolism rates of bacteria in the sediment, allowing the bacteria to break down complex molecules they would not be able to consume otherwise. When bacteria break down organic matter, it produces CO_2, protons, and electrons. The bacteria required more energy to breakdown the organic matter by using electron acceptors with high electric potentials, in the form of oxygen. Ideally, the bacteria donate electrons to oxygen molecules, which can combine with hydrogen to produce water.

However, when bacteria live in sediments, which are typically anaerobic environments, they are not able to easily access oxygen. Some bacteria can access electrons from the oxygen in the water column by using natural shuttles such as iron oxide materials (Li and Yu 2015). However, these electron transfers are weak due to low concentrations of electron mediating substances in the sediment (Li and Yu 2015). Similarly, some cable bacteria can form chains to reach the surface of the sediments (Schauer et al. 2014). However, in most cases, bacteria must transfer their electrons to less energetically favourable reactions, such as sulphate, which lowers the amount of energy they receive and inhibits their ability to break down difficult to degrade organic matter.

An MFC functions like common batteries. However, the chemistry in the MFC is catalysed by the metabolism of bacteria. An MFC is created by placing the anode into the sediment, an anaerobic environment, while the cathode is placed in the water column, an anaerobic environment. The following reaction, catalysed by the consumption of organic matter (CH_2O) by bacteria, occurs at the anode:

$$CH_2O + H_2O- > CO_2 + 4H^{++}\ 4e^-$$

The anode is the electron acceptor, which transfers the microbes' electrons from the sediments to the water column through a wire where the electrons are donated to oxygen. The following reaction occurs at the cathode:

$$4H^{++}\ 4e^- + 2O_2- > H_2O$$

By living on the MFC anode, microbes can utilize the reaction with the greatest electric potential and break down organic matter that cannot be broken down under anaerobic conditions or is decomposed slowly. Earlier research on MFCs focused on creating batteries that can produce a current to power another instrument necessary to monitor the site while cleaning up biotoxins (Santoro et al. 2017). Additionally, MFCs can be utilized by wastewater treatment plants to decompose organic matter, particularly sulfides, and produce electricity (Du et al. 2007). However, another use for MFCs is to use a similar design to increase rates of bioremediation.

9 Algae and Cyanobacteria for Wastewater and Sewage Treatment

Micro-algae such as eukaryotic algae and cyanobacteria are sustainable and energy-intensive for biological treatment process which is environmentally friendly and are used worldwide (Singh et al. 2015). Micro-algae use in wastewater treatment is cost-valuable and renewable source of biomass for the biological fixation of carbon dioxide (Almomani et al. 2019). Microalgae are historically seen as difficult and cost-effective to remove and cause problems that lead to create dangerous disinfection by-products. Algae have the potential to improve wastewater and wastewater treatment plant effluent and generate biomass for biofuels (Arbib et al. 2014). During wastewater treatment, algae integrated into the secondary treatment process as well as in tertiary treatment. During secondary treatment, algae need low aeration due to solar irradiation which is difficult due to turbid conditions (Humenik and Hanna 1970).

In the tertiary treatment process, it is cost-effective, and the generation of biofuels or other useful products may be offset. During tertiary treatment, the process has direct access to sunlight which improves to removal of nutrients that remained in secondary treatments in which algae is settled by other biosolids while in tertiary, it required additional harvesting (Van Den Hende et al. 2011). For drinking water safety, production of biofuel, or wastewater treatment, algae are used as a biomass in which chlorophyll is used to check the concentration of algae, and its growth. Chlorophyll can be quantified by using autofluorescence or absorption methods on the instruments (Held 2011).

10 Current Challenges

Along with advantages, several challenges are still hinder the implementation of wastewater and sewage sludge treatment related to industrial application as well as consumption of energy in the cultivation process. Pumping and Aeration systems are most conventional approaches for wastewater treatment are frequently used to culture micro-algae to create turbulent flow to enhance the gaseous exchange and environmental performance. Nowadays sewage sludge treatment is becoming a difficult strategy due to its cost-effective nature in terms of its constituents (Muhammad and Rohani 2011). Production of biorefinery from waste activated sludge offers advantages for sludge management in the future by adopting a treatment pathway for a sustainable production system and looking forward to future for value-added by-products. Acceptable challenges and issues which are associated with bio-refinery production from waste activated sludge included:

1. Enzyme and protein production is highly cost-effective in terms of heavy metal toxicity and pathogenic (Kalogo and Monteith 2008).
2. Selection of heavy metal tolerant microbial strains is needed to progress and recovery of metabolic products such as bio-pesticides, bioplastics, bioflocculants, and bio-surfactants need further optimization of operational parameters.
3. Feasible growth environment and wastewater matrix for treating waste-activated sludge with specific bioproducts should also be refined as it exerts direct influences on growth, functioning, and survival of microbial communities.
4. Purification and efficient work needed more development during the treatment of wastewater and would improve in overall biorefinery approaches and sludge management practices.
5. In an anaerobic digester, low temperature is also a crucial challenge because microorganisms need optimum temperature15–35 °C for their growth and multiplication and if there is any change from this range, then kinetics of the overall mechanism disturb (Malaeb et al. 2013; Bhatia et al. 2017).

Stabilization of sewage sludge to be used for arable land is a major challenge in both developed and underdeveloped world as it generally contains a good level of organic and inorganic pollutants and pathogenic microorganisms that can cause serious consequences for human beings, animals, and surroundings. After stabilization, it must be properly analysed for risk assessment to determine its safety profile. Bacterial communities may differ due to temporal and spatial factors so the determination of the functional potential of these communities according to prevailing climatic conditions, and soil type is also a serious challenge that requires specific attention of regional research institutes and organizations.

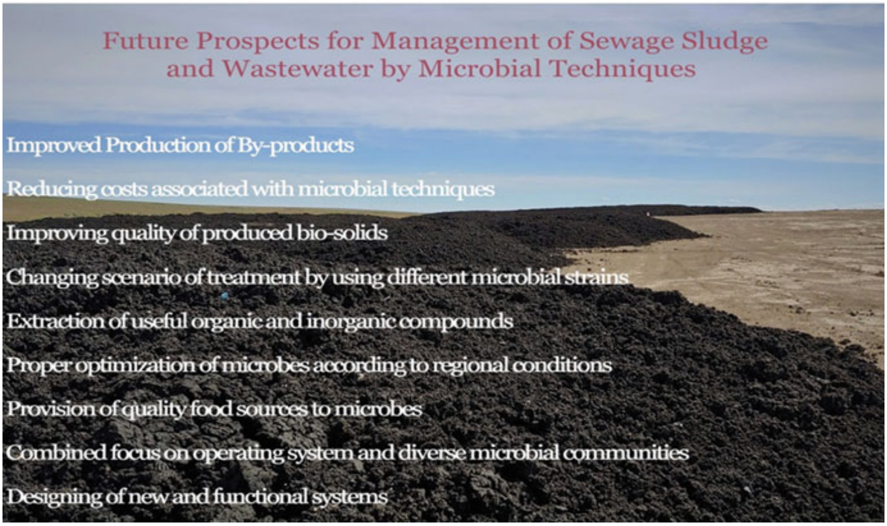
11 Future Prospects

The latest advancement in science and technology has greatly revolutionized the sewage sludge management practices over the past decades and thus there has been greater contribution for environmental protection, maximum positive and safe use of biosolids and residues for agricultural purposes, and human safety. However, the accelerated costs associated with the microbial techniques and other biological processes have always been a major concern and needs significant attention from scientific communities, policymakers, and institutional organizations.

Improved production of biogas, advanced dewatering techniques, controlled thermal, and landfilling processes are greatly being applied practically. Sometimes these costs may exceed 50% of the total amount as for the treatment of wastewater. Problems of high cost can be resolved by using reuse and recovery practices to hit the mark of sustainability. The sustainable management of sewage sludge revolves around six major practices such as improving the value of sewage sludge by various techniques (especially biological), beneficially using the compounds of organic carbon, and other inorganic compounds, decrease of total volume of sludge, recovering phosphates, and other essential nutrients from sewage sludge, changing the scenario of microbial treatment by using different strains, and combinations of different biological, physical, and chemical practices for sustainable sludge management (Picture 1).

Sustainable management of sewage sludge has become a serious issue around the globe and there should be direct and target-oriented studies to manage sewage sludge without causing any serious implications for human beings, animals, and environmental protection. Biological processes and the use of microbial techniques are greatly helpful for the biological conversion of chemical energy of the sewage sludge to good quality and methane-rich biogas. Sewage sludge contains nutrients in the form of proteinaceous materials as can be used as an exceptional plant fertilizer for direct application onto the soil. Therefore, a good revenue can be generated by using microbial and biological treated sewage sludge.

Sewage sludge is a precious source of essential nutrients and carbon contents and can be utilized as an amendment for improvement of soil health and overall fertility. But right integration of desired amount and providing safe and well-managed sludge



Picture 1 Future prospects for management of sewage sludge and wastewater by microbial techniques

to the growers and farmers is important to eliminate the hazards of toxicity. Even though microbial technologies and biological processes are significantly helpful to produce safe and high-quality products and end-products, but the safety profile of these products must be ensured to get maximum benefits. Moreover, the resulting products must be properly tested by following the regulatory measures and standards.

The sewage sludge contains different types and levels of pollutants such as endocrine-disrupting chemicals, pharmaceutical contaminants, nanoparticles, contaminants in personal care products, pesticides, fertilizers, and micropollutants. There is always a variable number of effluents in sewage sludge and the use of microbial techniques should be properly optimized according to the level of contamination and hazards. Moreover, the microbial niches also need proper optimization according to prevailing climatic conditions, and treatment conditions. There should be proper and well-documented efforts to interlink, and interconnect the energy, food, and water in the nexus system.

Management strategies should be optimized in such a way that there is no negative effect on the climate, environment, and ecosystem functioning. The protection of the ecosystem and climate is not only dependent on the quality of water but on productivity also. Therefore, there should be optimized and well-planned proposals for the nexus of microbial niches for the sustainable management of sewage sludge. Nexus of microbial niches should be significantly capable of removing both unknown and known pollutants.

The provision of quality and easily available food sources to different microbial species is a key target to ensure maximum removal efficiency by microorganisms. Provision of food source is essential for a diverse range of microorganisms such as polyphosphate accumulating organisms, denitrifies, nitrifiers, and heterotrophs. The microbial communities should be cultivated through an optimized series of aerobic, anoxic, and anaerobic reactors to increase the removal efficiencies. Currently, microbial techniques for the removal of different contaminants are not focused on the targeted removal of multiple contaminants so scientific communities should be more focused on the synergistic removal of different contaminants for safe and effective handling of sewage sludge.

There should be a significant focus on bioinformatics and novel microbial techniques for uncultured microbial functioning. Niches related to the novel functioning of microbes may have a greater level of variation than the conventional and cultured microbes so proper investigation about microbial interactions, diversity, and metabolic kinetics should be properly evaluated and studied. Further implementation of technological solutions as per community standards of microbes can help to produce significant beneficial results. The functioning of microbes for sewage sludge management and wastewater treatment processes can be greatly improved by the clarification of biological mechanisms. So, therefore there should be a good collaboration between scientific communities, and international organizations for data sharing and improved understanding and development of working standards.

A combination of long-term operating systems and diverse microbial communities can significantly help to discover unknown functions of microbes and can also help for the development and optimization of different strategies. Natural environments like intertidal zones can also provide alternate and are valuable sources for microbial functions, and metabolisms. Identification of microbial metabolism and functioning is important for combining proteomics, RNA, and DNA-based techniques for regulatory strategies and exploring the ecological functioning of microbes. There should be proper consideration for the regulation of amino acids, vitamins, and micronutrients along with elucidation of metabolic pathways and macronutrient cycles.

Furthermore, proper attention should be given to operational control processes and system designing. The designing of new functional systems must be capable of following scientific and technological rules to provide more time, space, and substrate ingredients for diverse functioning. Also, there should be a controlled and optimized focus to control environmental conditions to achieve efficiency and performance for different microbes. Interdisciplinary cooperation can also play a key role to achieve the purpose of sewage sludge and wastewater management.

12 Conclusion

Sewage sludges always contain a good level of bacterial diversity and the identification of bacterial community structures and chemical attributes is significantly important to target the desired efficiency of treatment and production of end products. There has been a good potential for the treatment of sewage sludge and wastewater by using microbial techniques. But this potential has not been fully explored due to the diversity of microbial species, their chemical attributes, and different functioning under different climatic and geographical conditions. A collaboration between researchers, scientific communities, and international students will be essentially helpful to achieve the goal of sewage sludge management on a sustainable basis.

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