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Bioreactors for Sludge and Wastewater Treatment: A critical review of processes and advancements

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Abstract

The management of wastewater and sewage sludge is of great significance for living a civilized life. Industrial and municipal wastes are among the major sources of sludge to the living vicinities especially in the urban areas. The physico-chemical properties of the sewage and wastewaters vary considerably from different sources. The development of bioreactors in the management of sewage sludge is a great technological step in the management of wastes emanating from different sources. The introduction of microorganisms is a key factor in the functioning of bioreactors. There are a variety of bioreactors manufactured, which have been effectively used to treat wastewater and sludge. The basic principle of bioreactors is to create such a conducive environment, which allows the optimal microorganisms for breakdown of the complex substances into simple products. Accordingly, the design and fabrication of the bioreactors are determining factors in their efficiency to waste disposal and management. In this review, the properties of sewage and wastewater and the types of various bioreactors introduced since old times to date have been discussed.

Keywords: Wastewater and sludge treatment, pollutants, bioreactors, microorganisms, effluent sources

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1. Introduction

Waste collection and its proper disposal are collectively called waste management. Since the advent of civilization, waste management has been a priority. Attempts have ever since been made to develop ways to manage waste without environmental implications. Numerous ancient urban centers were constructed with sophisticated drainage systems, primarily designed to facilitate the efficient removal of rainwater from the thoroughfares and rooftops. The utilization of drainage systems in ancient Rome is a notable illustration. The Cloaca Maxima, also known as the “Great Sewer”, was a substantial arched conduit transporting drainage water to the Tiber River. It was found to be associated with several additional surface conduits. According to research the Cloaca Maxima, a substantial stone edifice, is a testament to the early advancements in Roman engineering that have proven successful over time [1]. Despite privy vaults and cesspools during Middle Ages, a significant proportion of waste was indiscriminately disposed of in the gutters and subsequently washed away by rainfall. Water closets, commonly referred to as toilets, made their initial appearance in domestic dwellings during the early 19th century. It is worth noting that during this period, these facilities were commonly linked to cesspools rather than sewer systems [2]. The intolerable living conditions in densely populated areas rapidly ensued due to the presence of neglected and overflowing cesspools. The potential hazard to public health was apparent. The cholera epidemics in England during the mid-nineteenth century were found to have a direct correlation with the contamination of well water supplies. This contamination was primarily attributed to human waste from drains and urinal vaults. One of the sources of contamination was human waste. In the foreseeable future, it is anticipated that each public restroom within a metropolitan area will be mandated to possess an independent linkage to the storm drainage system of the respective city. Discharging sewage onto the adjacent land ultimately resulted in its subsequent entry into proximate aquatic ecosystems. Consequently, the issue of surface water pollution has emerged in the recent times supplies [3].

Introducing minimal quantities of sewage into a stream triggers the inherent self-purification capacity of the stream. Nevertheless, mere dilution process is inadequate in mitigating pollution due to the substantial waste generated in densely populated regions. This suggests cleaning or treating wastewater before its disposal is necessary. The construction of central sewage treatment plants was undertaken exclusively by the United States and the United Kingdom, preceding any other nation. Various treatment processes, including physical, biological and chemical methods, were employed since centuries to mitigate the concentration of pollutants in the sewage before its release into a nearby aquatic environment. Innovative sewage collection systems were devised in response to the concern regarding the amalgamation of rainwater and Sewage, marking the first advancements in this field since the 19^{th} century. The progress has resulted in a reduction in the influence of precipitation on the functioning of wastewater treatment facilities [4-7].

Sewage is a partially solid waste substance generated as a byproduct of the processing of urban wastewater. In the latter half of the 20^{th} century, regulations about the proper disposal of wastewater underwent a significant expansion and tightening in response to escalating environmental apprehensions. The treatment necessitated a higher level of intensity. An emerging trend involves the pre-treatment of industrial wastewater to mitigate the potential disruption caused by toxic chemicals in the biological processes utilized in sewage treatment plants. The advancement of wastewater treatment technology has facilitated the near eradication of sewage pollution. However, this form of care was often considered unnecessary because of its high cost. Currently, the prevailing norm in wastewater treatment involves the utilization of sizable, intricate, and energy-intensive facilities. Following increase in oil prices during the 1970s, the importance of energy conservation escalated as a crucial component in developing novel pollution control systems. Consequently, it became imperative to manage sewage disposal on land or underground whenever appropriate. Implementing these "low-tech" strategies for pollution prevention has the potential to not only result in energy conservation but also contribute to the processes of nutrient recycling and aquifer recharging [8].

The quantity of waste in wastewater directly impacts the volume of sewage generated. A bioreactor can extract a significant volume of liquid from the waste stream, enabling the activated sludge to treat the remaining liquid. A filtration device can be strategically placed near, below, or alongside the membrane bioreactors (MBRs). Within the boundaries of a bioreactor, a designated enclosure employed to subject wastewater to a biologically active milieu, the biomass consisting of bacteria and protozoa can metabolize and assimilate various constituents present in the untreated wastewater [9]. Implementing MBRs and other wastewater treatment reactors can potentially enhance the quality of agricultural water available to urban residents. The implementation of this bioreactor has the potential to enhance the operational efficiency of a municipal wastewater treatment facility within a given urban area. The MBRs and activated sludge processes can potentially treat solid waste. The bioreactor facilitates activated sludge treatment by eliminating water from the waste mixture. In this review, a detailed account of wastewater sludge with a particular focus on the use of bioreactors in the treatment of sludge and wastewater originating from various sources has been presented [10].

2. Management of wastewater and sludge

2.1 Historic outlook of wastewater management

Due to the inhabitants' residence in compact, nomadic societies, waste management challenges were infrequently encountered. The advent of sedentism and agricultural practices approximately 10,000 years ago marked the commencement of a distinct epoch. According to the Mosaic Law of Sanitation, before the emergence of advanced civilizations, individuals would excavate pits in the ground and conceal them following each utilization. The lack of available historical documentation poses significant challenges in ascertaining the state of health among individuals in ancient societies. Historically, wastewater treatment encompasses a tripartite procedure within the realm of wastewater administration. The stages are commonly denoted as tertiary, primary, and secondary treatment. It is imperative to remember that the initial treatment does not invariably eliminate all impurities. There is a notable reduction of approximately 60% in suspended solids and a decrease of 35% in biological oxygen demand (BOD) levels. The first treatment is administered before the second treatment. The second treatment method effectively reduces more than 85% of the BOD and suspended solids. Second-line treatment is often necessary in developed nations, including the United States. After the third level of treatment, it can be observed that more than 85% of the total solids and BOD are effectively reduced [11].

Disinfection is the concluding phase in wastewater treatment. It eliminates any remaining pathogens before the wastewater is released into a surface water source [12]. Usually, it is common practice to introduce liquid hypochlorite solutions or chlorine gas into the effluent within a contact tank for a short time. The process is conducted to cleanse the effluent. Due to the potential harm posed to aquatic organisms by residual chlorine in the effluent, implementing an additional chemical treatment process can effectively mitigate its presence. A wastewater treatment system's size and operational capabilities are contingent upon the quantity of water entering the system and the sewage generated by various residential, commercial, and industrial entities linked to it. Several factors need to be considered when determining the most suitable treatment facility, including the customer count, location, site-specific limitations, sewer connection availability, average and peak flow rates, wastewater properties, government-imposed effluent limits, technological feasibility, energy consumption, and operational and maintenance costs. These factors collectively influence the optimal choice between an on-lot, clustered, or centralized treatment facility**.** Urban and rural areas commonly discharge wastewater by directly releasing it into a surface water system. Subsurface disposal is more commonly observed in rural and suburban regions. Treating or purifying wastewater before reusing is important for maintaining water quality and safeguarding public health. Different levels of extraction are required for dissolved solids and biodegradable organics. It is also imperative to eradicate pathogenic bacteria. The necessity of neutralizing or eliminating plant nutrients, such as nitrates and phosphates, along with hazardous chemicals and industrial waste by using different approaches is pivotal [13].

Regional environmental factors and government regulations dictate the minimum level of wastewater treatment required. Establishing regulations about streams and the quality of their discharged water is of utmost importance. The formulation of these regulations is based on categorizing water based on its "maximum beneficial utilization." Streams are subject to various regulations that pertain to several parameters, such as the level of coliforms, turbidity, acidity, and the occurrence of hazardous substances. On the contrary, effluent standards delineate the specific characteristics of treated wastewater that are permissible for release into the environment from a sewage treatment facility. Typically, these regulations pertain to controlling BOD, coliforms, acidity levels, and suspended solids [14].

2.2 Modern approaches to wastewater management

The predominant techniques employed in wastewater treatment, including flocculation and coagulation, majorly depend on chemical agents such as aluminum chloride and polyelectrolytes. The combination of physical and chemical treatment methods generates significant sludge, posing adverse environmental effects. Many nations, in developed and developing countries, have promulgated rigorous policies and regulations on adequately managing and disposing of domestic and industrial wastewater. Numerous studies have ascertained that substantial advancements have been achieved over time. Contemporary methods employed for wastewater treatment include chemical precipitation [15], nanofiltration [16], algae treatment mechanisms [17], reverse osmosis [18], ion exchange [19], ultrafiltration [20] and biosorption [21]. In the subsequent paragraphs, an analysis will be conducted on several emerging trends. In recent years, many case studies have been undertaken to examine diverse strategies for wastewater treatment. Many of those strategies effectively focus on purifying industrial effluents. These studies eventually inferred that the presence of foul odors presents a noteworthy obstacle towards the wastewater membrane treatment. Various studies conclude conducting investigation on microbial fuel cells (MFCs) for wastewater treatment. The utilization of MFCs proves highly advantageous as it enables the harnessing of microorganisms present in wastewater to power industrial processes while concurrently facilitating the purification of wastewater together with energy generation [22]. Microbes present in wastewater oxidize the organic compounds to fulfill their energy needs. Consequently, the movement of electrons gives rise to the phenomenon known as an electrical current. Compared to alternative fuel sources for powering MFCs, wastewater has been established as the most sustainable choice due to its economically advantageous nature and organic composition. A wide array of exo-electrogenic bacteria demonstrate high efficacy in the oxidation of organic matter and transfer electrons to the anode of a fuel cell [23].

A recent report on the latest wastewater treatment methods revolved around utilizing algae for biosorption, nanofiltration technology and wastewater treatment [24]. The nanofiltration technique utilizes the process of membrane filtration. The central aspect of this method involves using bonding agents to exploit their capacity to induce the formation of cationic complexes containing heavy metal ions. The interaction between heavy metals in wastewater and agglomerated particles results in the formation of complexes. When molecules undergo a chemical reaction, the total mass of the resulting system is greater than the sum of the individual masses of the reacting molecules. This results in the contaminants being more prominent in size compared to the membrane pores utilized for their separation [25]. Nanofiltration offers several benefits, such as its notable energy efficiency, capacity to separate substances precisely, and potential to accelerate chemical reactions [26]. Nanofiltration is anticipated to be employed as a wastewater treatment method in the future. This process can be attributed to the inherent adaptability of the equipment utilized and the range of versatile materials employed in the process, [27]. Over the last five decades, the method for eradicating algae has been employed quite frequently. The underlying assumption is that aquatic microorganisms can mitigate the presence of detrimental substances including arsenic, selenium and zinc [28]. Various algae species, such as spirogyra, can accumulate substantial quantities of radioactive substances. Consequently, these algae possess the capability to be utilized in the treatment of wastewater derived from a diverse range of industrial processes. One of the key benefits associated with the utilization of algae for wastewater treatment is their significantly reduced environmental footprint [29]. The water purification method is considered highly environmentally sustainable due to its absence of anthropogenic chemical discharge into the surrounding ecosystem. By providing sustenance to these microorganisms in this manner, their continued existence in promoting the overall well-being of the ecosystem can be guaranteed. Another additional benefit of this approach is its promotion of the utilization of cost-effective and easily obtainable primary resources. Biosorption refers to a physicochemical phenomenon wherein wastewater contaminants are bound to the cellular structures of a specific biomass. This method involves the transfer of heavy metals from wastewater into biological materials through metabolically regulated uptake pathways. Living organisms subsequently absorb the metals [30]. One notable characteristic of this approach is its lack of dependence on the supplementary energy sources. The capacity of a solvent to eliminate contaminants is contingent upon the kinetic equilibrium and the surface area of the cellular sorbent, as contaminants exhibit affinity towards the cellular structure [31].

3. Wastewater and sludge characteristics

As previously mentioned, sludge and wastewater can be derived from diverse sources. Industrial sludge and wastewater, alongside municipal sludge and wastewater, exhibit discernible characteristics. Continue research into explore the parallels between sludge and wastewater is greatly warranted.

3.1 Physical properties of sludge and wastewater

The behavior of sludge and wastewater undergoes physical changes in response to the processes at the exhaust site. Determining wastewater's five primary physical properties is contingent upon the chemical and biological processes that transpire in diverse locations, which will be expounded upon in the subsequent discourse. The attributes encompass hue, turbidity, temperature, odor and foaming capacity.

3.1.1 Color

Both watercolors and mixed liquor suspended solids (MLSS) must be taken into account during the examination of sludge and wastewater [32]. Despite the increased difficulty in detecting color changes in systems that involve dye and a significant amount of colored input, is imperative to continuously monitor any such changes. If the MLSS is in a good health and experiencing growth, it depicts a brown hue. The observed brown coloration of the substance can be attributed to the existence of bacterial cells, biological polymers, and minute particles [33]. A lighter brown shade signifies a better biomass characterized by a lower concentration of biopolymers [34]. If the water exhibits a dark gray or black hue, emits an odor reminiscent of a septic tank, and contains sediment that has been present for multiple years, it is plausible that an issue about the circulation of air or the process of mixing may play. Individuals exhibit variations in color perception, and the presence of ambient light can influence one's perception of color. Consequently, it is imperative to remain vigilant for any alterations in color perception and diligently document one's observations. A robust microbial aggregate or biofilm, characterized by a brown coloration, is commonly observed within biologically sound sludge environments. Due to an extended duration of sitting, brown sludge exhibits reduced activity and a higher concentration of minuscule particles. The degradation of the biopolymer cohesion occurs in the aged grayish sludge. Black color exhibits a diminished capacity for dye absorption, increased septicity, and lower dissolved oxygen levels as compared to white [35].

3.1.2 Foam

Foam is produced when the surface tension of water changes [36]. Foam can be produced by microorganisms, biological polymers, and even certain influent surfactants [37]. Foam is an excellent indicator of microbial activity due to its close relationship with biological activity. However, it can be challenging to make this observation if there are many surfactants in the influent. Furthermore, foam is the most critical surfactant, which typically produces a white, consistent, dense appearance. When active bacteria are sprayed with water, they produce an unstable white foam. White foam often indicates that sludge and logs have just begun to grow. The brownish foam gradually acquires a portion of the color of the MLSS. When *Nocardia* sp. grows, it produces frequently dense, brown, stable, and greasy foam. It thrives in long-chain fatty acids rich environments, where sludge has been present for an extended period. When there is foam, much of it must be removed and discarded. A gray foam resembling pumice could indicate old sludge or conditions with insufficient oxygen [38].

3.1.3 Odor

The olfactory perception emanating from a place that has been recently occupied is known by a faint resemblance to either a mild detergent or a subtle oiliness. It is due to the production of various gases in the wastewater. Hydrogen sulfide (H_2S) is responsible for the foul-smelling odor of the sewage [39]. H_2S, characterized by its potent and displeasing scent, is generated during the anaerobic decomposition of food. Due to its poor compatibility with wastewater, the H_2S is discharged into the atmosphere, emitting an unpleasant odor. This results in polluting the environment [40]. Apart from amines and mercaptans, other compounds have the potential to generate odors within treatment plants. At lower concentrations, olfaction exhibits negligible impact; however, it can induce adverse physiological responses such as illness, emesis, and diminished fluid consumption at elevated concentrations. It is reported that the malodorous emissions are a result of the presence of volatile sulphur compounds within sludge cakes. These compounds are released during the process of wastewater treatment. It is a significant health hazard for plants, animals, and microbes [41].

3.1.4 Temperature

The temperature of sewage plays a crucial role as it influences both the kinetics of chemical reactions and the longevity of aquatic organisms. On the other hand, the temperature of Sewage exhibits seasonal fluctuations. The temperature of this water is marginally higher than that of the groundwater. The elevated temperature observed in Sewage is attributed to organic matter decomposition. The temperature of effluent entering the processing plant or bioreactor may have grave effects on the microorganism. Thus, a favorable temperature for the sewage sludge contained in wastewater should be around 35ºC or lower for proper processing and disposal [42]. The temperature ranges for different microorganisms are presented in Table 1.

3.1.5 Turbidity

The quantification of colloidal and domestic suspended matter in waste discharges and natural waters can be achieved by assessing water transparency [43]. The measurement of turbidity can be achieved by employing nephelometric turbidity units (NTU). To ascertain the turbidity levels, a comparison is made between the light scattered by the sample and the standard suspension, which shows similar scattering patterns. Formazin suspensions are widely regarded as the benchmark for measuring turbidity [44]. The amounts of solids in sludge are given in Table 2.

3.2 Chemical properties of wastewater and sludge

The composition of sludge and wastewater varies significantly from place to place and from source to source. Various substances, such as nutrients, heavy metals, pollutants, bacteria, solids, as well as dissolved and particulate matter, have the potential to contaminate wastewater [45]. Many suspended solids also comprise part of the wastewater and sludge. Substances such as dissolved nitrogen, phosphorus, and oxygen can modify wastewater's pH and chemical composition. Wastewater exhibiting highly acidic or alkaline properties typically indicates industrial waste, necessitating pre-treatment measures before discharging into the sewer system [46]. Dewatered sewage sludge typically comprises a substantial proportion of organic matter ranging from 50% to 70%, alongside mineral components amounting to 30% to 50% [47]. Additionally, this sludge may contain 1% to 4% inorganic carbon [48]. It is noteworthy that dewatered sewage sludge harbors a considerable quantity of recoverable nutrients, including micronutrients. The chemical properties of sludge and wastewater are readily observable [49].

3.2.1 Organic matter

Sewage generally comprises a significant quantity of organic material. The quantity of organic matter depends upon the type and manner of sewage disposal employed. Organic matter in sewage can manifest in various forms, including dissolved substances, suspended particles, colloidal matter, or sediment, which may be up to 35%–40% [50].

3.2.2 Nutrients

Individuals typically experience a loss of sodium and chloride in the form of NaCl on daily basis, which ranges from 8 to 15 g. This loss predominantly occurs through sweat and urine excretion. This suggests that domestic wastewater, originating from sources like showers and toilets, contains higher chloride levels. In addition to the nitrogen content ranging from 3.4% to 4.0% and phosphorus content ranging from 0.5% to 2.5%, the sewage exhibits a significant abundance of various other vital nutrients. Sulfite is a metabolic byproduct generated by anaerobic bacteria in sewage, facilitating the breakdown of organic substances without oxygen. In addition, depending upon their concentrations, micronutrients also form part of sewage sludge and effluent water [51]. Regarding nitrogen, sewage comprises diverse nitrogenous compounds, encompassing organic nitrogen, ammonia, nitrite, nitrate, and many other nitrogenous compounds, although in minor quantities [52]. Raw sewage typically contains a minimal amount of inorganic nitrogen. On the contrary, the predominant nitrogen content found in organic septic waste originates from non-living sources. The nitrite concentration in Sewage does not exceed 1 mg/L due to its production during the conversion of ammonia (NH_3) to nitrate (NO_3). The sewage treatment facility underwent a process of converting NH_3 and nitrite (NO_2) compounds into NO_3 compounds as the outcome [53].

3.2.3 Biological oxygen demand (BOD)

Sewage exhibits a significant BOD due to its substantial content of organic substances. The levels of BOD in sewage can vary, depending on the degree of dilution and contamination. BOD levels can be less than 100 mg/L in cases where the sewage is highly diluted. Conversely, when the sewage is highly concentrated and contaminated with industrial waste, BOD levels can exceed 600 mg/L [54]. Sewage exhibits diminished levels of dissolved oxygen due to the presence of numerous microorganisms, and organic substances that are susceptible to decomposition. There are instances in which sewage is not relevant. Another factor contributing to the diminished dissolved oxygen levels in sewage is its poor solubility in oxygen, which is about 95% of that observed in clean water [55].

3.2.4 pH

Industrial effluent and sewage contain many chemical compounds affecting the wastewater's pH from various sources. Mainly, sewage water manifests pH in a slightly alkaline range. With a change in the pH of wastewater, there occurs a change in the media surface attributes and matrix of wastewater. The bases (e.g., sodium hydroxide or caustic soda) or acids (e.g., hydrochloric acid) control the pH during wastewater treatment [56].

3.2.5 Oxidation-Reduction (O-R) potential

The oxidation-reduction potential of sewage indicates whether it exhibits a predominantly oxidizing or reducing nature. The O-R method is widely regarded as a highly effective approach for evaluating the state of wastewater treatment facilities. For example, tripling filters necessitate an operational-reliability potential ranging from +2 mV to +600 mV. The optimal redox (O-R) potential range for anaerobic treatment processes, such as sludge digestion, is typically specified to be within the range of -100 to +200 [57].

3.3 Biological properties

Water can facilitate the proliferation of various microorganisms, including bacteria, viruses, and protozoa. Abdel-Raouf et al. [55] reported that individuals who are ill or asymptomatic carriers have a substantial excretion of pathogenic microorganisms, which ultimately find their way into sewage systems. Most of these substances are safe for treating sewage systems involving living organisms. The presence of pathogens, such as those responsible for cholera, typhoid, tuberculosis, hepatitis viruses, dysentery-causing protozoa, and worm eggs, has been identified in the garbage. The assessment of sewage disinfection efficacy often relies on the measurement of total coliform organism removal. A wide array of microorganisms has been discovered within sewage samples. These microorganisms can modify the biological processes occurring in sewage and other types of wastewaters. Although the environment is abundant with microorganisms, a vast majority of them are not only innocuous but also advantageous to human beings as they contribute to the biological remediation of wastewater [58].

3.3.1 Bacteria

Sewage comprises two distinct categories of bacteria: gut- and sewage-dwellers. Non-pathogenic intestinal bacteria are a regular constituent of the microbial community residing in the gastrointestinal tracts of both humans and animals. The gut-bacteria have excreted waste material within the sewage. Some of these bacteria include *Clostridium perfringens*, fecal coliforms, and fecal streptococci [59]. Pathogenic bacteria commonly found in the intestines, such as *Shigella*, Vibrio cholera, and *Yersenia enterocolitica*, can infiltrate sewer systems through the excrement of individuals infected with these bacteria. Sewage contains bacteria that are classified explicitly as sewage bacteria. Sewage comprises a diverse range of microorganisms, including aerobic and anaerobic species. Airborne bacteria play a crucial role in the aerobic decomposition process of organic matter. Some commonly observed anaerobic bacteria include *Clostridium sporogens*, Bifidobacterium and *Peptococcus*. Prominent examples of methanogenic bacteria encompass *Methanobacterium* and *Methanosarcina*. The airborne microbial community encompasses various bacterial species, such as *Zeoglea remigera*, *Nocardia*, *Flavobacterium*, *Achromobacter* and *Nitrosomonas*. The predominant organism observed in trickling filters is *Z. remigera* [60].

3.3.2 Algae

Algae play a crucial role in aquatic ecosystems by serving as primary producers [26]. Nevertheless, it is essential to acknowledge that they have the potential to contaminate water through various highly perilous means. The augmentation of algal nutrient levels in water by utilizing organic effluents can induce the proliferation of specific algal species, leading to extensive surface growths commonly referred to as 'blooms.' These blooms harm water quality and limit utilization. An example of this phenomenon is the rapid growth of algae in water contaminated with organic waste, which can substantially impact the water's inherent ability to cleanse itself. A wide array of algal species are recognized for their capacity to induce pollution, posing a threat to various aquatic organisms, including humans and fish. Recent findings have revealed the presence of algae, specifically *Chlorella phormium* and *Ulothrix* etc. in Sewage. Algae are utilized in trickling filters within sewage treatment plants [61].

3.3.3 Fungi

Fungi, present in higher quantities in wastewater, possess advantageous properties, which can be harnessed for various applications [62]. Different fungi exhibit remarkable adaptability to diverse and challenging environments, such as municipal and industrial wastewaters, heavily hydrocarbon-contaminated sites, acidic substrates, and environments with low oxygen levels. The production of laccase and peroxidase by fungi through enzymatic processes is remarkable. The enzymes can break down a wide range of chemical compounds. *Sporotricum* and *Fusarium* are two fungal species that contribute to the filtration process. Based on available reports, these fungi were identified within sewer systems [63].

3.3.4 Viruses

The viruses are omnipresent and can multiply in diverse ecological settings. In addition to aquatic environments that receive treated and untreated wastewater, ecosystems are designated explicitly to accommodate these substances. The occurrence of sewer overflow is often attributed to viral pathogens that infect the gastrointestinal tracts of individuals. [64] observed that infected individuals generally experience a reduction in the range of 105 to 1012 viral particles per gramme of fecal matter. Non-pathogenic viruses can be found in various water sources, such as those used for agriculture, animal husbandry, and seasonal surface runoff. Various human pathogenic viruses, including rotavirus, hepatitis A and E, and poliovirus, have been detected in Sewage and can be transmitted through the excrement of infected individuals [65].

3.3.5 Protozoans

Individuals experiencing gastrointestinal disorders have the potential to introduce protozoa into their fecal matter, consequently leading to the contamination of sewage systems. Pathogenic protozoa such as *Entamoeba histolytica*, *Giardia*, and *Balantidium coli* are notable examples. The trickling filter is known to harbor a limited number of protozoa, specifically *Vorticella* and *Opercularia* [66].

4. Factors leading to the production of wastewater

Wastewater, commonly known as greywater, encompasses all discharged water from residential or commercial premises. Both residential and commercial sewage are commonly observed. Industrial Sewage is employed to dispose of wastewater generated by chemical processes or factories, while domestic sewage is utilized to eliminate wastewater originating from residential dwellings. After the separation process, both wastewater categories undergo primary and secondary treatment.

4.1 Where does wastewater come from?

Wastewater can be generated from various structures encompassing plumbing fixtures, such as sinks, bathtubs, toilets and showers. Wastewater refers to the contaminated water that collects in gutters or originates from the roofs. Daily, individuals dispose of diverse forms of wastewater, such as those originating from their bathing and sanitation facilities, into subterranean sewer systems beneath thoroughfares and municipal infrastructure. Residents residing in regions lacking access to public sewer systems must manage the disposal of their domestic wastewater using private sewage systems, including septic tanks and treatment plants. Transportation of wastewater to designated treatment facilities through sewer systems is common among individuals. Discarding kitchen fats, oils, and grease is not recommended by pouring them into the drain and the sewer system. So, to prevent the accumulation of cooking oils and grease in sewer systems, it is advisable to refrain from disposing of these substances, as they can lead to pipe blockages and the formation of fatbergs.

4.1.1 Sewage from homes

Wastewater comprises water that is discharged from various structures, including residential, commercial, and industrial establishments. Sewage is derived from industrial facilities, household sinks, showers, laundry appliances, and toilets. An example of domestic wastewater is the water derived from various household fixtures, including the kitchen sink, shower, toilet and washing machine, as given in Table 3. The mean intensity of household wastewater varies over the day, night, and seasons, in alignment with water usage patterns, individual lifestyles, habits, dietary choices, and socioeconomic status. The primary factor responsible for differences in water consumption lies in the variations observed among households. Affluent communities exhibit higher levels of water consumption in comparison to poor communities [67].

4.1.2 Sewage from factories/industries

The term "effluent" is commonly employed to describe wastewater that is discharged into surface waters through a sewer or an industrial outfall. There is a potential scenario in which the wastewater may not have undergone any treatment. A wide range of industries generate industrial wastewater, including sectors producing food and beverages, extracting oil and gas, and manufacturing chemicals [56]. The utilization of factory wastewater is observed in the manufacturing processes of footwear, apparel, electronics, and automobiles. Industrial wastes may be solid, semi-solid or liquid in form. They may be hazardous (some types of which are toxic) or non-hazardous wastes. Industrial waste may pollute the nearby soil or adjacent water bodies, and can contaminate groundwater, lakes, streams, rivers or coastal waters. There are many types of industrial wastewater from different industries and the contaminants; each sector produces its own particular combination of pollutants (Table 4).

4.1.3 Sewage from storms

By definition, sewage from storms is the water from rains or snow melting. At the time of heavy rain, the water overflows into the homes, gardens and streets. Under extreme conditions, the storms may lead to emission of industrial effluents to mix with water thus deteriorating its quality. In such conditions, the sewers are laid to manage excess water. Storm sewers are underground pipes specifically engineered to gather and convey water from various sources, including snow melting, rainfall, and the excess water from garden hoses. The water is discharged into catch basins, lakes, and rivers through sewers. The storm sewer drain is commonly positioned directly beneath the sidewalk. Beneath it is a tunnel or piping system for reservoir purposes. The second alternative is deemed appropriate for water transportation to a distinct destination. It is imperative to differentiate between a storm drain and a conventional sewer. The improper disposal of human waste, whether through discharge into storm drains or flushing down toilets, possesses the capacity to introduce contaminants into adjacent freshwater reservoirs [68].

4.2 The handling of wastewater and sludge

There are four distinct methods employed for the treatment of wastewater, namely physical treatment, chemical treatment, biological treatment, and sludge treatment.

4.2.1 Physical wastewater treatment

Presently, physical processes are utilized in the treatment of wastewater. Solids can be extracted through screening, sedimentation, or skimming techniques. Chemicals are not utilized in this particular procedure. Spending insoluble particles in water is of utmost importance in wastewater treatment. Once the solid particles have undergone precipitation and settled at the bottom, extracting the purified water can commence [69]. Another efficacious physical technique for water treatment entails the introduction of air. The introduction of oxygen into the solution is facilitated by the passage of an air bubble through the water [70]. Filtration is commonly used as the third approach to remove potentially harmful substances effectively. Filters possess the ability to effectively cleanse sewage through the removal of solid particles and various impurities. Sand is extensively employed in the construction of filters. When applied to wastewater, this technique efficiently removes the visible layer of grease floating on the surface [71].

4.2.2 Biological wastewater treatment

This is a centuries old approach and is equally valid even today to biologically treat wastewater and to make is reusable. Biological treatment involves using microorganisms to metabolize and break down the organic constituents present in wastewater. The subject matter is composed of three distinct elements: aerobic process, anaerobic process and compositing. Firstly, the aerobic process in which microorganisms use oxygen in producing carbon dioxide. Bacterial organisms engage in the process of organic matter decomposition, resulting in the production of carbon dioxide, a compound that plants can utilize. The process involves the utilization of oxygen [72]. Secondly, the anaerobic process in which fermentation converts waste into a valuable substance at a designated temperature. Anaerobic reactions are capable of taking place in the absence of oxygen. Methane gas is usually produced under anaerobic conditions during organic matter decomposition. Untreated wastewater may also generate CH_4 if anaerobic condition is maintained there. Thirdly composting is a natural process by which microorganisms decompose organic matter into simpler nutrients. It is also an effective way of eliminating toxic chemicals from the sewage sludge. This is a commonly employed approach for aerobic wastewater treatment, and entails the utilization of carbonaceous substances, such as sawdust, as carbon sources [73]. The secondary treatment effectively removes a significant portion of solid particles from wastewater. It is undeniable that dissolved nutrients, such as nitrogen and phosphorus, have the potential to persist within the solution. On a large scale, bioreactors are used for the biological treatment of sludge and wastewater [74].

4.2.3 Chemical water treatment

The procedure, as indicated by its vocabulary, involves the introduction of chemical compounds into the water. Chlorine, a chemical with oxidizing properties, is commonly utilized to eradicate bacteria present in water, thereby diminishing its usability. Ozone is an additional oxidizing agent that is employed for wastewater purification. Restoring water's pH to 7 can be achieved by introducing either an acid or a base. The phenomenon being referred to in this context is commonly known as neutralization. The potability of the water is ensured due to the presence of chemicals that effectively impede the proliferation of microorganisms. Different chemical processes are used to remove targeted contaminants or to convert them into stable oxidized end products that can be safely disposed of to receiving water streams without any adverse ecological effects or risks to human health [75].

Table 1. Temperature classification of biological processes

Type	Temperature range (ºC)	Optimum temperature range (ºC)	Temperature range (ºF)	Optimum temperature range (ºF)
Psychrophilic	10–30	12–18	50–86	53.6–64.4
Mesophilic	20–50	25–40	68–122	77–104
Thermophilic	35–75	55–65	95–167	131–149

Source: Metcalf and Eddy [76]

Table 2. Solids concentration in various sludge types

Sludge type	Solids concentration (%)
Primary sludge	5–8
Waste activated sludge	0.5–2.0
Fixed film waste sludge	3–10
Primary and waste-activated sludge	2.5–4.0
Primary and fixed film sludge	3–5
Aerobically digested sludge (thickened)	1–2
Anaerobically digested sludge (thickened)	6–12

Source: Droste [77]

Table 3. Color characteristics of wastewater from household sources

Color of wastewater	Household source
Yellow water	Human urine
Brown water	Human faeces with flushed water (can include paper if used)
Black water	Human faeces (brown water) mixed with urine (yellow water) in general: wastewater from toilets. It contains human waste and can be a public health risk if not treated properly.
Gray water	Water used in kitchen, bathroom including sink, bath, shower and laundry etc., or any water that has been used at home except water from toilet.

Source: Samwel [78]

Table 4. Water Pollutants by the Industrial Sector

Sector	Pollutant
Iron and steel	BOD, COD, oil, metals, acids, phenols, and cyanide
Textiles and leather	BOD, solids, sulfates and chromium
Pulp and paper	BOD, COD, solids, Chlorinated organic compounds
Petrochemicals and refineries	BOD, COD, mineral oils, phenols, and chromium
Chemicals	COD, organic chemicals, heavy metals, SS, and cyanide
Non-ferrous metals	Fluorine and SS
Microelectronics	COD and organic chemicals
Mining	SS, metals, acids and salts

Source: Hanchang [79]

5. Methods and types for treating wastewater and sewage sludge

There are various methods of treating sewage sludge and wastewater, as given below.

5.1. Treatment methods

The thickened sludge under consideration is derived from two separate tanks: the primary sludge tank and the excess sludge tank. The treatment of sludge commonly involves four primary methods: thickening, digestion, dewatering, and disposal.

5.1.1 Thickening

Thickening is anyway involved in all schematic treatments of disposal sludge and wastewater. The initial phase in sludge treatment is called thickening, as it is not feasible to handle sludge in its diluted form, consisting of a combination of solids and water. Frequently, a gravity thickener tank is utilized for this objective. By utilizing a thickening agent, it is possible to decrease sludge volume to less than 50% of its initial size. Instead of depending on the force of gravity, the process of dissolved-air flotation can be employed to increase the concentration of solids. Through the process of exposing the solids to the surface, a layer of thickened sludge is generated. The sludge thickening process is commonly carried out in a tank-like structure which is known as a gravity thickener. A thickener has the potential to drastically minimize the total quantity of sludge to at least less than half of its initial amount. Dissolved-air flotation technique is another gravity method. Here the bubbles of air take the solids compounds towards the surface, and the thickened sludge accumulates [80].

5.1.2 Digestion

The process of sludge digestion entails the transformation of organic solids into inert substances through the action of microorganisms. The eradication of pathogens, reduction in total solids mass, and promotion of sludge dehydration or drying are facilitated through digestion. In addition to these considerations, it is worth noting that high-quality potting soil typically lacks any discernible odor and possesses an aesthetically pleasing appearance, resembling digested sludge. After the initial stage of treatment, the wastewater is subjected to agitation in an aeration tank using aerobic microorganisms. Biological solids are produced due to organic substances' digestive and decomposition processes. These solid particles tend to coalesce into larger structures referred to as flocs [81]. Most large-scale sewage treatment facilities commonly employ the process of anaerobic digestion as a means of decomposing organic matter in an oxygen-deprived environment. Before further processing, the sludge is subjected to a thickening procedure involving the application of heat and agitation within a hermetically sealed container for several days. A yield of approximately 5% dry solids is obtained. Bacteria that generate acid can break down complex molecules, such as lipids and proteins, into smaller, water-soluble components. The fermentation process of smaller molecules facilitates the production of diverse fatty acids. Following this, the sludge is transferred to a secondary tank, wherein a greater quantity of bacteria facilitates the decomposition of the dissolved substances into biogas, a mixture of carbon dioxide and Methane [82].

The application of heat can lead to the decomposition of large molecules. The discussed process is known as thermal hydrolysis, representing an advancement compared to the traditional two-step anaerobic digestion procedure. This process is executed as an additional stage preceding the process of digestion. The usual protocol initiates with a dewatered sludge with an approximate dry solids content of 15%. The sludge and steam mixture are subjected to pressure within a reactor operating at a temperature of 165°C (330°F) for approximately 30 minutes [83]. The process is initiated by combining sludge and steam within a pulper. The sludge is expeditiously introduced into a "flash tank," where the sudden reduction in pressure causes the cell walls of most of the solid material to rupture, following the release of a portion of the steam generated during the hydrolytic reactions to provide for the pulper. The downward displacement of sludge persists. After cooling and slight dilution, hydrolyzed sludge is subsequently directed to the second phase of anaerobic digestion [84].

5.1.3 Dewatering

Drying digested sewage sludge before its disposal in landfills is a common practice. Despite containing a considerable proportion of water (up to 70%), dewatered sludge is more easily handled for processing due to its solid form. The implementation of sludge-drying beds enables the removal of moisture. A layer of desiccated sand serves as the substrate for applying a mixture of processed organic waste, known as sludge, which is subsequently exposed to ambient conditions for dehydration. The desiccation of sand occurs because of the combined effects of precipitation and gravitational forces. The water is collected through an underground network of pipes and subsequently conveyed to the plant's roots for recycling. The solids content of the "sludge cake" can attain a level of 40% following a drying period of approximately six weeks. Subsequently, employ a pitchfork or front-end loader to extract it from the sand. The act of covering sand beds with glass during cold or wet weather conditions has the potential to speed up drying. Due to the substantial spatial requirements, drying beds for water removal are infrequently employed in densely populated regions. There is no necessity for the utilization of sludge-drying beds. Alternative options, such as a belt filter press, centrifuge, or rotary drum vacuum filter, can replace the mentioned equipment. Compared to traditional beds, these mechanical systems exhibit enhanced efficiency in accelerated sludge drying and reduced space requirements. However, it is customary to commence the sludge conditioning process at the outset. During this phase, chemical agents are incorporated into the liquid sludge to enhance drainage and promote the formation of solid clumps.

5.1.4 Disposal

After treatment, sewage sludge is typically disposed of by dumping it onto land. Septic tanks are a prevalent method of ecologically eliminating sewage. These tanks are uncommon in densely populated areas or significant metropolitan areas. Desiccated sludge is suitable for disposal in a sanitary landfill. It can be applied to agricultural land to benefit from its fertilizing and soil conditioning properties. Agricultural fields do not utilize sludge due to its potential presence of hazardous industrial chemicals [85]. Burning or combustion of the sludge is an option in urban areas where suitable land for its disposal is scarce. Following the combustion process, only ash is produced and any moisture content is eliminated. Even though the ash must be discarded, the smaller quantity reduces the cost. When combusting sewage sludge, air pollution controls must be carefully considered. To maintain clean air, filters and scrubbers are required [86].

5.2. Treatment types

During the initial stage, the removal of macroscopic particles takes place. Activated sludge is employed during the secondary stage of wastewater treatment to eliminate biodegradable organic matter and colloidal particles effectively. During the third stage, the extraction process focuses on removing nutrients, particularly nitrogen and phosphorus, that microorganisms have not metabolized. Before its discharge into a stream or river, the water undergoes disinfection during the fourth stage (Fig. 3). In all, there are three major types to treat wastewater and sludge, as elaborated below:

5.2.1 Primary treatment

It is one of the classical methods to treat wastewater and sludge. Primary treatment is the gravitational sedimentation process aimed at separating and removing denser solid particles. The utilization of trenches and pits constitute the initial approach to primary treatment. Throughout the Middle Ages, these methods have been used to eliminate denser particulate matter before its application, with the intention of ameliorating the soil properties and averting the occurrence of blockages. The excavation of trenches and pits emerged as one of the earliest prominent approaches to disease treatment. In their study, Chatzakis et al. [84] identified the presence of sedimentation tanks within several archaeological sites, including the Minoan-built city of Tylissos, the Palace of Knossos, and the Hagia Triada.

In the initial stage of treatment, the removal of particles that possess the ability to either ascend to the surface or descend to the bottom is undertaken. Comminution, grit removal, screening, and sedimentation are among the mechanical processes that have been investigated. Screens are constructed using elongated and slender metal bars, subsequently positioned near one another. These devices inhibit the buoyancy and obstruction of pumps and pipes by effectively impeding the movement of wood, rags, and other sizable objects. Contemporary industrial facilities are equipped with automated machinery designed to cleanse the screens, while waste materials are promptly disposed of through on-site burial methods. The comminutor is a device that can effectively grind and shred any waste material that bypasses the screening process. Ultimately, the fragments are retrieved via the processes of flotation or sedimentation. Grit chambers are elongated and narrow reservoirs designed to facilitate the separation of solid particles from wastewater, encompassing various substances such as sand, coffee grounds, and eggshells, through a controlled and gradual hydraulic flow. Sand in water expedites the degradation of pumps and other machinery within industrial facilities. Storm events can transport substantial quantities of silt, sand, and gravel from urban areas with combined sewer systems, thereby intensifying the imperative to eliminate these particulate matters. Sedimentation tanks in sewage treatment facilities employ grit chambers and screens to eliminate solid particles that persist in the water effectively. These storage areas, commonly referred to as "primary clarifiers", allow for a two-hour period during which the water can undergo gravitational settling. Once the sewage has traversed the container, the solid particles undergo sedimentation and accumulate at the lowermost region. The mechanical scrapers facilitate settling solids, commonly called primary or raw sludge, in a linear trajectory along the tank's bottom. For sludge to be effectively extracted using a pump, it must first be deposited into a designated hopper. Surface-skimming devices effectively remove grease and other buoyant substances from the water's surface [87].

5.2.2 Secondary treatment

It is also among the widely used wastewater treatment methods. During the secondary treatment process, various microorganisms facilitate the conversion of organic carbon in wastewater into carbon dioxide, water, and energy, which can subsequently be utilized for regrowth. Metcalf and Eddy [72] categorize secondary treatment into two primary classifications. The first type is attached growth, which refers to the growth of biofilms—the other type is floating growth, which pertains to activated sludge. In the context of attached growth systems, microorganisms adhere to a solid substrate, such as a rock or plastic material, and subsequently establish a population on its surface to metabolite the sludge. This phenomenon facilitates the evolutionary and developmental processes of organisms. The presence of an aerated biofilm leads to a reduction in the BOD. The BOD in a suspended growth system diminishes due to the continuous agitation of wastewater and biomass. Most solid particles are reintroduced into the process following their removal during the subsequent steps of sedimentation and filtration.

a. Attached Growth: During the transition from the 19^{th} to the 20th century, there was a significant increase in the acceptance and recognition of the concept that microorganisms could purify wastewater. According to Lofrano and Brown [3], the trickling filter was initially devised by Edward Frankland, who in 1870 established the fundamental principles of soil filtration. This suggests that the deceptive filter can be attributed to France. The initial implementation of a trickling filter occurred in Salford, England, in close proximity to Manchester in 1893. According to a study conducted by Stanford University in 1976, in 1895 urban and rural areas across the UK implemented diverse forms of trickling filters to treat sewage. The trickling filter utilized in contemporary times has not been officially granted a patent.

***b. Suspended growth-activated sludge process*:** Preliminary investigations were undertaken at the Lawrence Experimental Station, located in Lawrence, Massachusetts, to ascertain the efficacy of aerating wastewater in the removal of contaminants. To attain the desired effluent quality, the researchers conducted experiments utilizing different wastewater treatment techniques within a draw-and-fill reactor, which operates like a sequencing batch reactor [88]. The term "activated sludge" was assigned by the individuals involved in its production based on the premise that the process revitalized the sludge. Scientists were previously unaware of the ability of multiple microorganism species to degrade carbonaceous pollutants into carbon dioxide, water, and energy for subsequent growth over a significant duration.

The initial reception of trickling filters in the United Kingdom impeded the widespread adoption of activated sludge processes. Nevertheless, upon their arrival in the United States, they swiftly gained significant popularity, with numerous plants being among the pioneers in wastewater treatment. The utilization of activated sludge processes has witnessed substantial growth in the United States, while its implementation in the United Kingdom has been sluggish. The attainment of this objective was stipulated by the Clean Water Act of 1972, with the requirement of employing secondary treatment methods [89].

5.2.3 Tertiary treatment (Advanced treatment)

The level of environmental awareness is increasing among the inhabitants of developed countries. The increased public interest in contemporary medical practices has been observed in parallel with advancements in diagnostic technology. After removing carbonaceous pollutants during the secondary treatment process, many facilities redirected their attention toward preventing eutrophication. An extensive network of treatment plants or a singular treatment facility is necessary to eliminate nitrogen and phosphorus [90].

6. Bioreactors as emerging technologies in wastewater and sludge treatment

The research on the development of wastewater technologies has been ongoing for decades. The development of modern wastewater treatment bioreactors has come of age and is successfully used. Due to the implementation of more rigorous water quality regulations, a considerable number of antiquated wastewater treatment facilities necessitate upgrading and modernization. Nevertheless, attaining this objective is frequently challenging due to the limited scope for expansion. The efficacy of treatment has improved without necessitating additional land due to advancements in novel techniques. Several examples of advanced wastewater treatment technologies include the membrane bioreactor, the integrated fixed film activated sludge (IFAS) process, and the ballasted floc reactor. A bioreactor is a vessel employed to conduct a range of chemical and biological reactions, particularly those involving fermentation. The primary objective of a closed system is to effectively remove waste products and decomposing matter that arises from the proliferation of microorganisms. The system exhibits sufficient ventilation, mobility, temperature and pH regulation, and airflow. Water treatment professionals have been actively working towards enhancing environmental regulations and legislation and implementing established technologies to achieve water quality objectives and ensure the protection of public health. Simultaneously, organizations have experienced significant changes in reaction to emerging challenges, including but not limited to population growth and climate change.

6.1 Bioreactor infrastructure

A bioreactor necessitates the inclusion of the subsequent components. The initial step involves agitating the tube to homogenize the cells and medium. The subsequent stage, aeration, is executed by employing anaerobic fermenters to introduce oxygen. Moreover, the ability to manipulate variables such as liquid volume, Temperature, pH, pressure, oxygenation, and nutrient supplementation. Furthermore, the fourth aspect to consider is sanitation, which involves the consistent upkeep of cleanliness and the implementation of sterilization measures. Exclude the medium or cells. Bioreactors can generate antibiotics, metabolites, and biomass.

6.2 Bioreactor design

The operational mechanisms and design of a bioreactor are subject to multiple factors, such as the volume of output, the market value of the product, the ideal conditions necessary for its production, and the organism's productivity. The utilization of a well-designed bioreactor enables the achievement of excellent outcomes while optimizing resource utilization. A bioreactor comprises a comprehensive range of systems, including an agitator system, an oxygen delivery system, a foam control system, and various lines responsible for reactor filling and emptying, cleaning and sterilization, temperature and pH regulation, among others.

In the initial stages, ensuring that the acidity level remains within an acceptable range is imperative. Furthermore, no substances with the potential to cause harm must be introduced into the fermentation medium. Additionally, the material must possess the ability to endure steam sterilization procedures. First and foremost, the material must exhibit the ability to endure variations in pH levels and increased pressure. The bioreactor's capacity is significantly influenced by its intended purpose. Various bioreactors are available, catering to different needs, such as small-scale fermentation processes or large-scale industrial applications. The range of dimensions extends from the diminutive microbial cell, which measures only a few cubic millimeters, to the giant fermenter employed in laboratory settings, which typically has a volume of 100 to 1000 milliliters. Beyond that, there are fermenters at the pilot level, which typically range from 0.3 to 10 cubic meters, and at the plant scale, which can vary from 2 to 500 cubic meters.

6.3 Bioreactor's principle

Reactors are automated devices that can transform biomass into commercially viable products. The applications of biocatalysts extend beyond enzymatic synthesis. A bioreactor plays a crucial role in bioconversion and biotransformation processes as it creates an ideal setting for cultivating microorganisms and synthesizing metabolites. The requirements of developing organisms can influence the design and construction of a reactor.

6.4 Bioreactor types

A great variety of bioreactors exists ranging from pilot-scale to large-scale development to manage sludge and wastewater. So important bioreactor types are discussed below.

6.4.1 Continuous stirred tank fermenter

This bioreactor type depicted in Fig. 1 is widely used in industrial applications. The impeller or agitator refers to components integral to operating a continuous stirred tank bioreactor. The central shaft, which is cylindrical and driven by a motor, supports them. The uniform gas distribution across the vessel is achieved by integrating the sparger with impellers, commonly called agitators. Stirred tank bioreactors are widely preferred by many individuals owing to their ability to operate continuously within the fermenter, minimal maintenance needs, and ease of construction and cleaning are important attributes of this bioreactor type.

6.2.2 Airlift fermenter

Airlift reactors commonly utilize gas-liquid or gas-liquid-solid contact devices. An alternative designation for this entity is a tower reactor. Implementing an airlift mechanism within a bioreactor reduces fluid volume by half, leading to improved internal force equalization, oxygen transfer, and flow. Gas sparging is limited to a solitary zone within a two-zone system, as depicted in Fig. 2. The gas is discharged through the riser, while the downcomer does not employ gas. The utilization of aerobic bioprocessing technology involves implementing airlift bioreactors to control the movement of liquid within a self-contained recycling system. This equipment possesses several advantages, such as its low energy consumption, cost-effectiveness, simple construction without agitators or moving components, and easy cleaning process.

6.2.3 Bubble column fermenter

The bubble column fermenter employs a cylindrical vessel equipped with a gas sparger to introduce gas bubbles into a suspension comprising either a liquid or a mixture of liquid and solid components. Air or gas is introduced into the column's base through metal spargers equipped with small apertures, metal pipes with perforations, or metal plates with perforations. The rate at which gas flows and the rheological properties of the fluid play a crucial role in determining the extent of oxygen mixing and other performance parameters. The vessel's fundamental design can be modified, and mass transfer can be improved by integrating internal components such as horizontal perforated plates, corrugated sheet packings, and vertical baffles. The design and implementation of these reactors exhibit a straightforward construction methodology, necessitating minimal maintenance efforts and boasting negligible life-cycle costs. Fermentation and biological wastewater treatment are two biochemical processes that utilize reactors equipped with bubble columns. It is also employed in various petrochemical, biochemical, and chemical processes (Fig. 3).

6.2.4 Fluidized-bed fermenter

The size of the particle-filled beds is decreased within the bioreactor. This approach mitigates common challenges encountered in packed bed reactors, such as blockages, substantial reductions in liquid pressure, channeling phenomena, and bed compaction. The function of a distributor pump is to facilitate the introduction of reactants into the reactor, thereby enhancing the fluidity of the bed.

The catalyst is strategically located at the base of the reactor in an aseptic manner. Minute particles carried by the fluid hinder the motion of cells within these reactors. As a consequence, there is an augmentation in the delivery of nutrients, oxygen, and mass. Bioreactors that utilize liquid-suspended biocatalysts, such as immobilized cells, microbial flocs, or enzymes, can effectively facilitate reactions. This particular catalytic reactor offers several notable advantages when compared to alternative options. These include enhanced temperature stability, streamlined catalyst regeneration processes, automated and uninterrupted operations, and reduced solid-gas contact durations (Fig. 4).

6.2.5 Packed bed fermenter

Utilizing a packed bed reactor facilitates the achievement of combining solids and liquids. The utilization of this substance is prevalent within the industrial sector, and it possesses the capacity to either catalyze or remain inert. The arrangement of the bed, commonly represented as a column, is dictated by factors such as the reaction rate, temperature, and pressure decrease. A biocatalyst can be found either on the surface or within the solid matrix of the fermenter. The two operational modes of the system include trickle flow and submerged operation, which may or may not involve the presence of airflow. Chemical processing operations that heavily rely on packing bed reactors, alternatively referred to as fixed bed reactors, encompass various processes such as separation, distillation, stripping, and absorption. Packed-bed bioreactors facilitate air entry into the system using a sieve that securely holds the substrate. This reactor offers numerous advantages, including its user-friendly interface, efficient catalyst conversion rate, cost-effectiveness in construction and operation, enhanced reactant-catalyst interaction, and ability to function under elevated temperatures and pressures. In packed bed reactors, the movement of cells is hindered by particles of significant size. These granules are absent in the liquid. While the design and operation of a packed bed reactor can generally be considered a straightforward procedure, it is essential to acknowledge that certain complexities may arise (Fig. 5).

6.2.6 Photobioreactor

This photobioreactor refers to a type of fermenter or sealed light-emitting diode (LED) system that operates using solar energy (Fig. 6). In general, the light reception systems are contained within the planar structures or cylindrical structures of photobioreactors, which are fabricated exclusively from transparent materials such as plastic or glass. Both airlift and centrifugal pumps can be utilized for medium movement in the solar receivers of this bioreactor. Photobioreactors typically function continuously, maintaining a consistent temperature of 37ºC for a significant duration. Astaxanthin and β-carotene are derived from photosynthetic microalgae and cyanobacteria cultivated in photobioreactors.

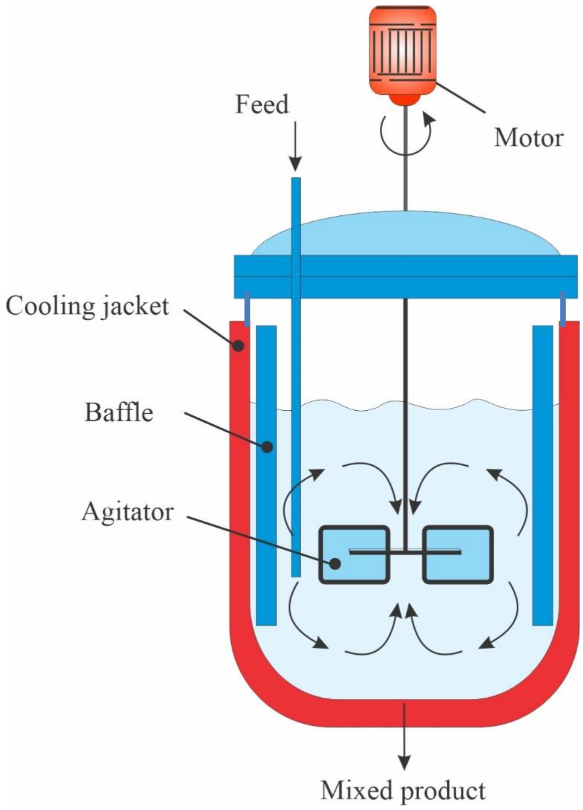

Figure 1. Continuous stirred tank fermenter (Adapted from Tavoosi et al.) [91]

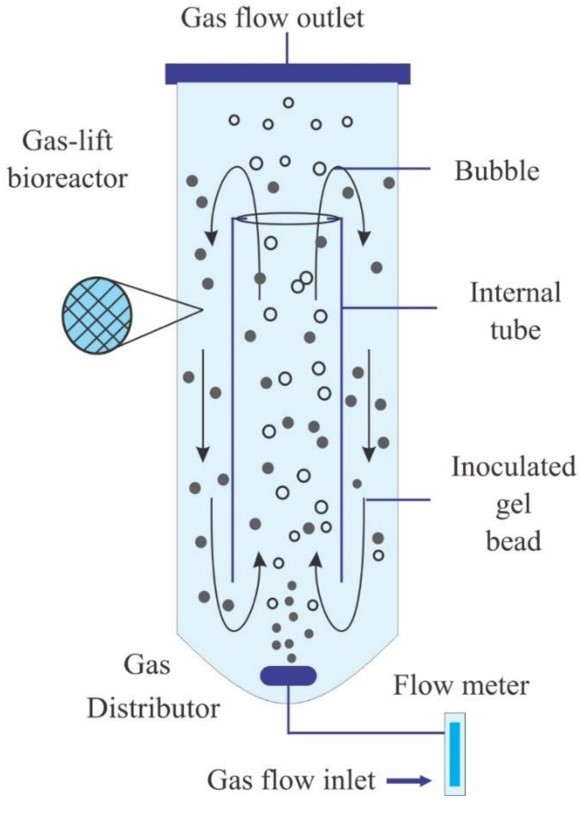

Figure 2. Airlift fermenter (Adapted from Siegel and Robinson) [92]

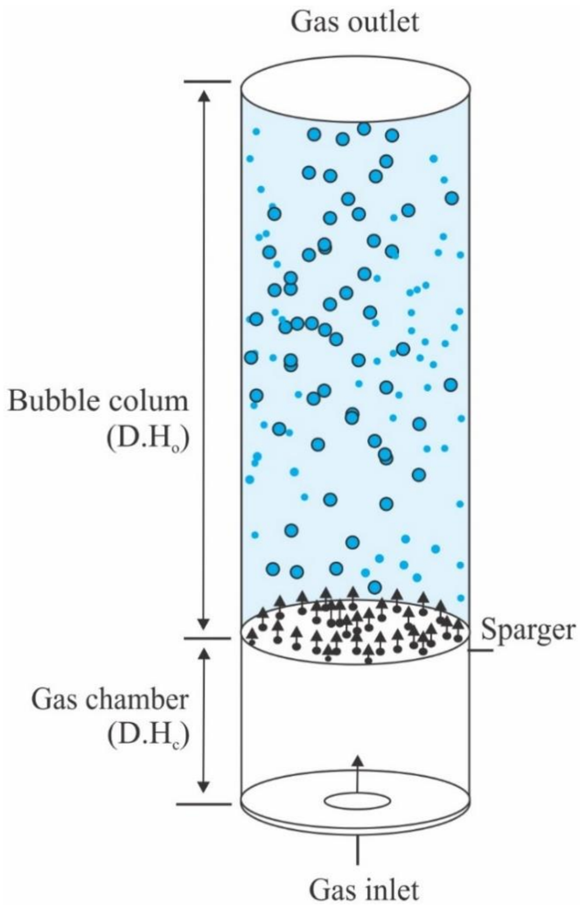

Figure 3. Bubble column fermenter (Adapted from Wilkinson et al.) [93]

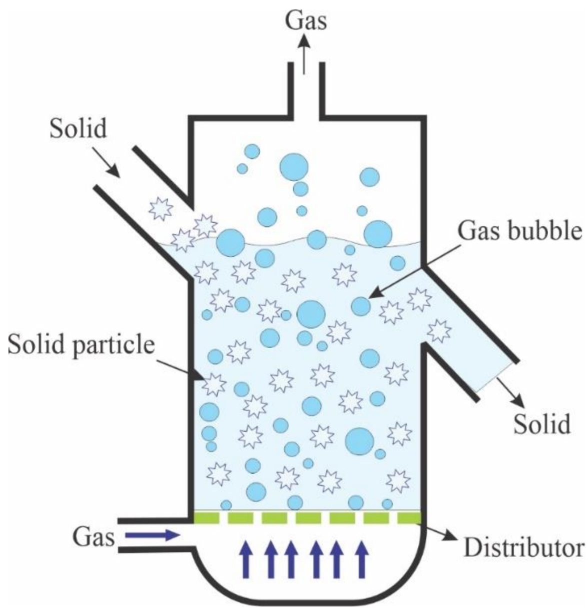

Figure 4. Fluidized-bed fermenter (Adapted from Kowng) [94]

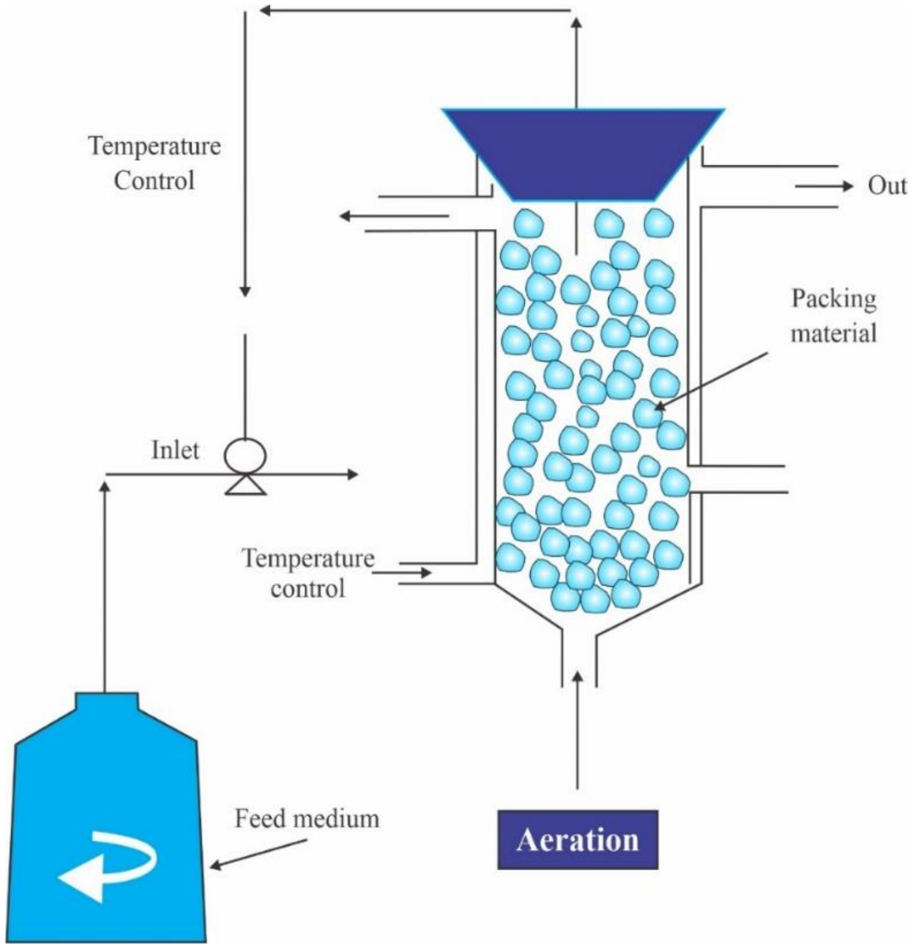

Figure 5. Packed bed fermenter (Adapted from Siegel and Robinson) [92]

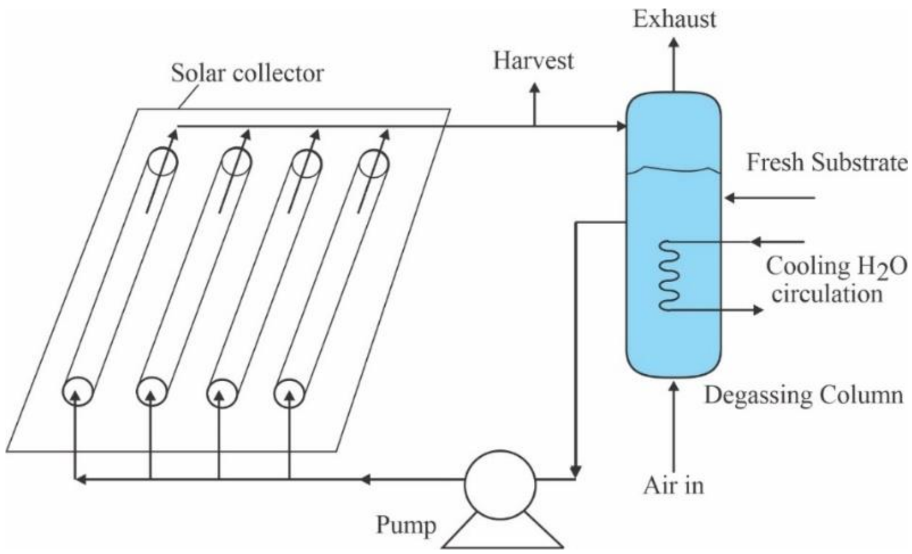

Figure 6. Photobioreactor (Redrawn from Sinha et al.) [95]

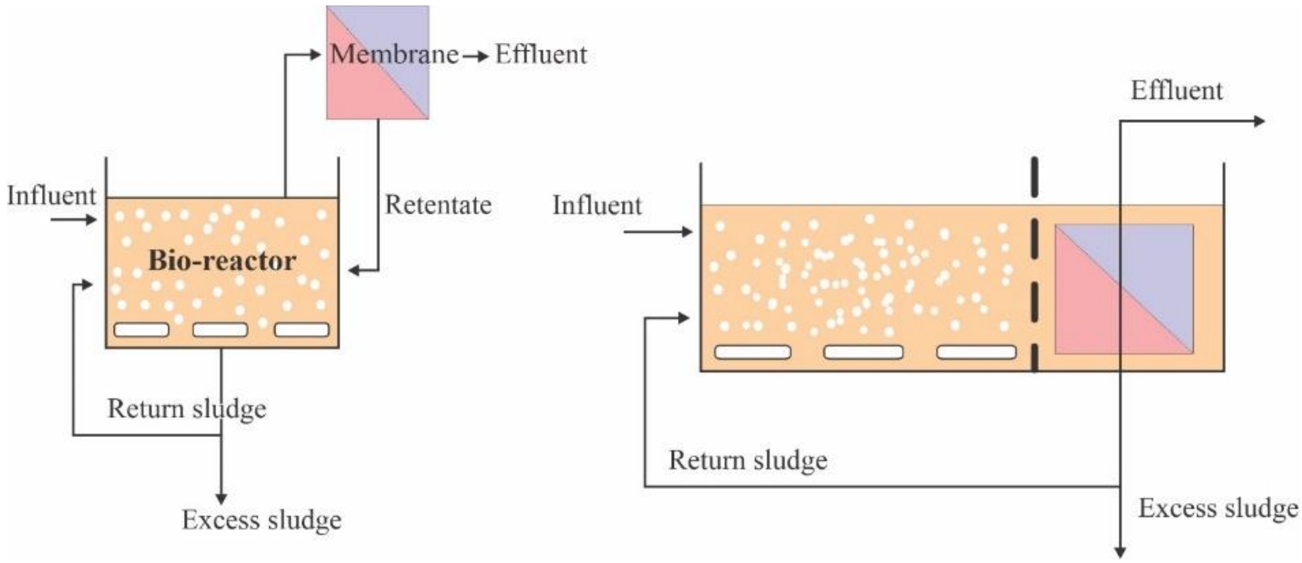

Figure 7. Membrane bioreactor (Conceived from Andersen et al.) [96]

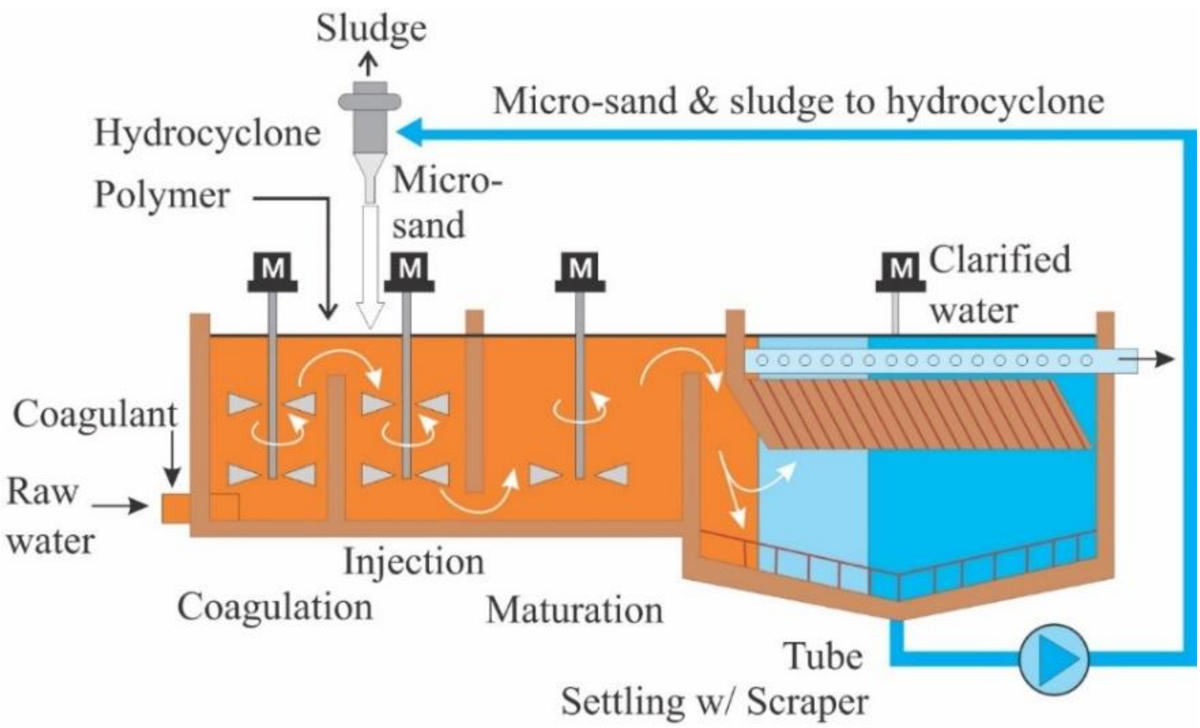

Figure 8. Ballasted floc bioreactor (Redrawn from Krüger published in Capodaglio) [97]

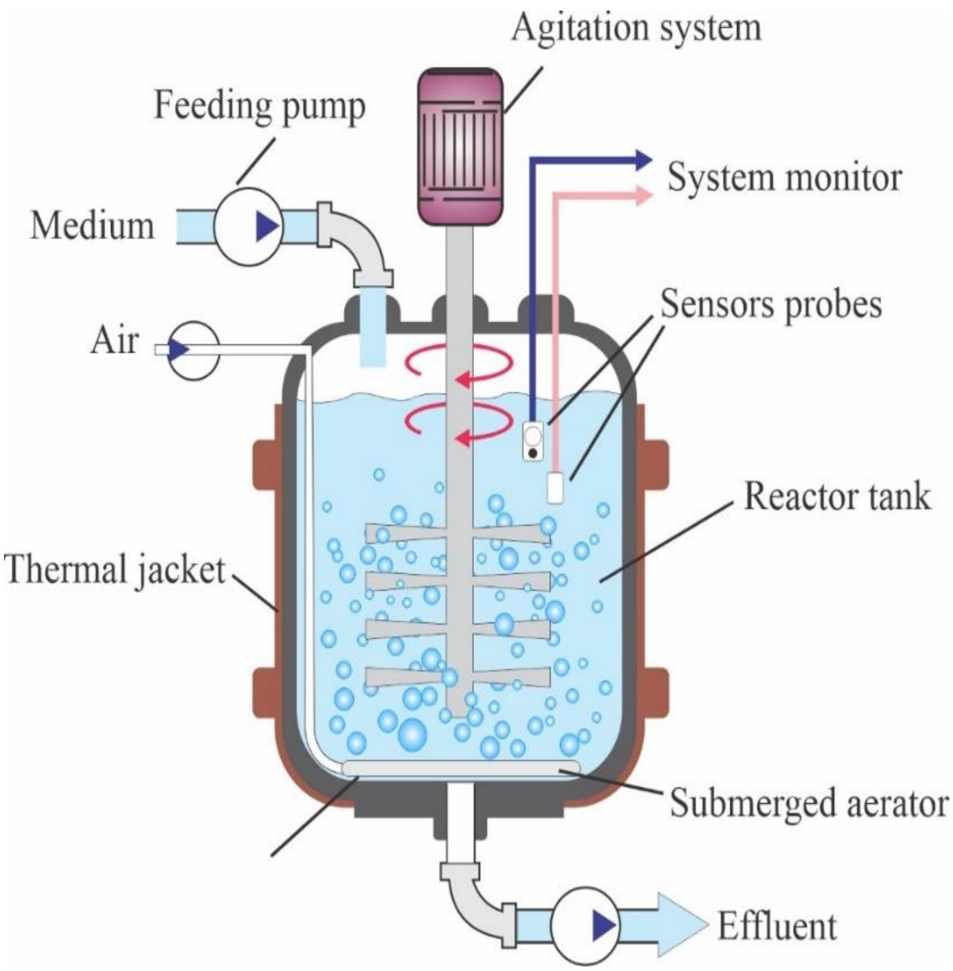

Figure 9. Continuous stirred tank bioreactor (Adapted from Saran et al.) [98]

6.2.7 *Membrane bioreactor*

The membrane bioreactor (MBR) process combines filtration, secondary clarification, and aeration within a single tank. It reduces the number of land stages necessary for treatment, decreasing the total from three to two. The membrane bioreactor system effectively removes surplus nutrients, suspended solids, and organic substances by integrating traditional filtration methods with membrane treatment. In this arrangement, the membranes are immersed within a biological reactor that facilitates airflow. The membrane's pore diameter can be modified within 0.35 to 0.4 µM range. The benefits of utilizing this bioreactor are enhanced when pure oxygen is present. One of the advantages includes utilizing biological treatment systems, which exhibit efficient performance in rapid operation and compact control over chemical oxygen demand (COD) and microorganisms (Fig. 7).

6.2.8 *Ballasted floc bioreactor*

The sedimentation rate of suspended solids is enhanced by using sand and a polymer, which aids in aggregating solid particles into more giant conglomerates referred to as flocs. The process of directing sand toward the outer wall of a hydro-cyclone can be achieved through centrifugal force. It involves introducing water at an acute angle near the apex of the cylindrical apparatus. This technique achieves the segregation of sand and organic matter. The sand accumulated at the lower section of the hydro-clone is reintroduced into the reactor through the force of gravity. Solids are separated from wastewater by utilizing biological aerated filters, which involve the implementation of a contact surface for biological treatment. The introduction of air-infused fine bubbles expedites the process, whereas the act of backwashing serves to cleanse the media. A biological aerated filter necessitates a spatial expansion of only 15% compared to a conventional activated sludge system (Fig. 8).

6.2.9 *Aerobic stirred tank bioreactors*

The most popular type of bioreactor for treating wastewater. The base of a stirred-tank reactor is commonly designed with a curved or cylindrical shape to facilitate efficient mixing of the reactor's contents (Fig. 9). These bioreactors ensure oxygen availability during the process.

7. Future Challenges

In the early 20th century, it seemed that industrialized nations had successfully addressed most health concerns from water contamination. However, it is essential to note that a considerable portion of the population in developing nations continues to face challenges in obtaining safe drinking water and adequate sanitation infrastructure. Individuals often resort to defecating in roadside ditches or utilizing makeshift receptacles such as buckets in the absence of conveniently accessible restroom facilities. The issue of inadequate sanitation in Kibera, a slum in Nairobi, Kenya, has gained international recognition due to "flying toilets." The lack of adequate public restroom facilities necessitates that individuals resort to using plastic bags to dispose of their bodily waste, subsequently discarding them in public thoroughfares. It can be likened to how waste is disposed of in middle-class households in Europe and other continents. Improvements in the design and efficiency of bioreactors is a future challenge in the wastewater treatment and sludge disposal.

8. Conclusions

With the rapidly increasing human population, the problem of waste disposal has aggravated enormously. This menace is especially more daunting to the environmental sustainability in the developing countries, where the addition of wastewater and sludge in massive quantities has great environmental and health implications. A speedy handling and management of wastewater and sludge is therefore a priority area of research all over the world. There are various sources and treatment means to get rid of excess of wastes originating from different sources. Among the classical means, the physical and chemicals methods have been popular in the past. Currently, the development of bioreactors is a great step forward in this regard. In addition, the selection of efficient bacteria for use in the bioreactors is also of great importance. To date a variety of bioreactors have been introduced with differences in their design and waste disposal efficiencies. There is still a need to introduce more efficient bioreactors with convenience in their operations.

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