Review on Wastewater Treatment Technologies

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Abstract

Nowadays, water resources are becoming increasingly scarce and many of them are polluted by anthropogenic sources such as industrial purpose, agricultural waste and household. Therefore, the treatment of wastewater remains a critical need before leaving it to natural water streams. The main purpose of wastewater treatment is to remove the various contaminants that presence in the wastewater such as suspended solids, organic carbon, nutrients, inorganic salts, heavy metals, pathogens and so on. The ultimate goal of the wastewater treatment is to provide the protection in terms of human health and environmental aspect. In this article, the use of wastewater treatment methods such as biofilm technology, aerobic granulation and microbial fuel cell are discussed briefly.

Introduction

Water resources are becoming increasingly scarce around the world due to the growing imbalance between freshwater availability and consumption, therefore the access to clean and safe water has become one of the major challenges of our modern society [1]. Water demand is keep increasing due to the following reasons:

- Increasing of population and migration to drought prone regions;
- Rapid industrial development and increasing water use per capita;
- Climate change leading to changing weather patterns in populated areas [2]
On the other hand, the water quality is threatened by the presence of a large number of pathogens [3] and anthropogenic chemicals that entering the urban and rural water bodies [4]. Discharges of wastewater from municipal and industrial treatment plants have been recognised as one of the major factors of aquatic pollution around the world [5]. In many developing countries, the bulk of domestic and industrial wastewater is directly discharged into water streams without going through any treatment processes or after primary treatment only [6]. Even a highly industrialised country such as China, approximately 55% of their sewage was discharged without any treatment [7]. The discharge of untreated wastewater to the water bodies without any treatment processes will lead to several environmental problems such as:

- Untreated wastewater which contains a large amount of organic matter will consume the dissolved oxygen for satisfying the biochemical oxygen demand (BOD) of wastewater and thus, deplete the dissolved oxygen of the water stream required by the aquatic lives;
- Untreated wastewater usually contains a large amount of pathogenic, or disease causing microorganisms and toxic compounds, that can dwell in the human intestinal tract thus threatening the human health;
- Wastewater may also contain certain amount of nutrients, which can stimulate the growth of aquatic plants and algal blooms, thus, leading to eutrophication of the lakes and streams;
- The decomposition of the organic compounds present in wastewater can lead to the production of large quantities of malodorous gases [8].

Therefore, the treatment of wastewater is a must before leaving it enters the natural water bodies. Different physical and chemical treatment methods have been reviewed for the treatment of wastewater such as biological degradation, ion exchange, chemical precipitation, adsorption, reverse osmosis, coagulation, flocculation, etc. All these treatment methods have different performance characteristics and also different direct impacts on the environment. This review will particularly discuss the application of biofilm technology, biogranulation and microbial fuel cell (MFC) for the treatment of wastewater.

**Biofilm technology**

Definition of biofilm itself is simply defined as communities or clusters of microorganisms that attached to a surface [9-10]. Formation of biofilm could be achieved by a single or multispecies of microorganisms that have the ability to form at biotic and abiotic surfaces [9].

As a general, there are few steps that important for development of biofilm, which starting with the initial attachment and establishment to the surface, followed by maturation, and finally, the detachment of cells from surface [9-11].
Figure 1: Process of biofilm development [9]

According to Watnick and Kolter [11], the formation of a bacterial biofilm is a same with community that is built by human. First, the bacterium must approaches closely before form a transient attachment with the surface and/or other microorganisms that formerly attached to the surface. This step of transient attachment allows the bacterium to search a place before adapting it. After the bacterium has finally settled down, it will form a stable attachment and associate into a microcolony, which is the bacterium has chosen the neighbourhood to live. Finally, the building of biofilm is established and irregularly, the biofilm-associated bacteria will detach from biofilm surface. The uses of biological treatment process have taken into placed compared to physical and chemical method in terms of their efficiency and economy [12]. One of the biological methods that have been realised to overcome the bioremediation problems is biofilm. According to Decho [13], biofilm-mediated bioremediation hands a capability and safer option to bioremediation with planktonic microorganisms. The reason behind this is because the cells in a biofilm have a high potentially to survive and adapt towards the process as they are protected by the matrices. Moreover, microbial consortium in the form of biofilm has the ability to decolourise and metabolise dyes since there are intrinsic cellular mechanisms that will bring about the degradation or biosorption of dyestuffs [11].

Advantages:
Biofilm offers a proficient and harmless option to bioremediation with planktonic microorganisms since the cells in biofilm have a highly chance of adaptation and survival, particularly in unfavourable conditions. This situation is due to the matrix that actually acts as a barrier and protects the cells within it from environmental distress [13]. Extracellular polymeric substances or EPS have significant towards the growth of biofilm which it appears that to be a part of protective mechanism for biofilm community. Wingender et al. [14] reported that EPS can minimise the impact
of modification in pH, temperature, and concentration of toxic substances. Biofilm can have very long biomass residence times when treatment requires slow growing organisms with poor biomass yield or when the concentration of wastewater is too low to sustain growth of activated sludge flocs [15].

**Application in wastewater treatment:**
Biofilm has becoming an interest subject to be explored, especially in the perspective of wastewater treatment, therefore, many studies has performed in order to achieve and gain understanding towards of the utilisation of biofilm to remediate the environment. Aerobic fluidised bed reactor, rotating biological contactors, aerobic membrane bioreactor are a few applications of biofilm reactors that have been invented to treat various condition of wastewater produced by the industrial. A summary of biofilm reactors that are used treating wastewater is showed in Table 1.

<table>
<thead>
<tr>
<th>Description</th>
<th>Type of wastewater</th>
<th>References</th>
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<tr>
<td><strong>Aerobic membrane bioreactor (MBR)</strong></td>
<td>functions as dual mechanism which membrane filtration occurs along with biodegradation processes water and small solution molecules pass through the membrane while solid materials, biomass, and macromolecules are retained in the reactor</td>
<td>Can treat high-strength synthetic wastewater [16]</td>
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<td><strong>Rotating biological contactor (RBC)</strong></td>
<td>operates by attaching microorganisms to an inert support matrix to form a biofilm support matrix and a sequential disc configuration is placed partially or totally submerged in the reactor and it will rotates around a horizontal axis slowly where the wastewater flows through into it</td>
<td>Can treat high-strength synthetic wastewater with chemical oxygen demand (COD) concentration up to 12000 mg/L [17]</td>
</tr>
<tr>
<td><strong>Anaerobic–aerobic granular biofilm bioreactor</strong></td>
<td>granular biofilm bioreactor consists of an upflow anaerobic sludge bed (UASB), having an aeration column or sparger placed in the middle of the reactor anaerobic and aerobic populations of the biofilm co-exist closely in the same reactor offers a good strategy to complete mineralisation of highly substituted compounds</td>
<td>Treat various chlorinated pollutants [18]</td>
</tr>
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Anaerobic-aerobic fixed film bioreactor (FFB)

- combination of two fixed-film bioreactor with arranged media (anaerobic and aerobic) connected in series with recirculation system gives advantages as less sensitivity to environmental variations and higher growth rate due to the used of immobilised cells on the surface of the media.

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<th>Treat wastewater that have high content of oil and grease</th>
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<tr>
<td>Anaerobic-aerobic fluidised bed reactor</td>
<td>Eliminates organic carbon and nitrogen from municipal wastewater</td>
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**Integrated anaerobic-aerobic fluidised bed reactor**

- use a cylindrical fluidised bed with pulvserised pumice-stone as support material for microorganisms to attach aeration is performed by four cylindrical fine bubble membrane diffusers offers good stability despite variations in organic load and delivers short start-up time for operation.

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**Limitations:**
There are several limitations of biofilm towards the implementation in wastewater treatment. The limitations are [21]:

- Biofilm formation on carriers poses problems leading to long start-up times;
- Overgrowth of biofilms leads to elutriation of particles;
- Control of biofilm thickness is difficult;
- Liquid distributors for fluidised systems are costly for large-scale reactors and pose problems with respect to clogging and uniform fluidisation.

**Aerobic Granulation Technology**
The improvement to certain drawbacks of biofilm has led to the invention of a novel microbial self-immobilisation processes called biogranulation at the late 1990s [22]. The granular sludge generated via biogranulation approaches have higher biomass retention and reusability, broader selection of bacterial strains for plausible bioaugmentation and higher microbial density with millions of bacteria cells per gram of biomass [23]. Biogranulation can generated two types of granular sludge which were aerobic granular sludge (AGS) and anaerobic granular sludge (AnGS), in which both of them can be developed in a fixed sequencing cycle of feeding, reacting, settling, and decanting under a single sequencing batch reactor (SBR) system [24]. However, the AnGS exhibited several disadvantages such as long start-up period, required strictly anaerobic environment, relatively high operating temperature, unsuitable for low strength organic wastewater, and low efficiency in the removal of nutrients (Nitrogen and Phosphate) from the wastewater [25]. Meanwhile the AGS
was able to overcome all the drawbacks of the AnGS as mentioned, therefore increased the effectiveness of the AGS in treatment of raw industrial wastewater. The AGS was regarded by some researchers as suspended spherical biofilm that included microbial cells, inert particle, degradable particles and extra cellular polymeric substances (EPS)[26]. Aerobic granulation may be initiated by the microbial self-adhesion, since the bacteria cells were not likely to aggregate naturally due to the repulsive electrostatic forces and hydration interactions among them[27]. The granular sludge possessed an excellent settling property compared with the conventional floc sludge and therefore enabling high biomass retention and dense microbial structures for withstanding high-strength organic wastewater and its shock loading[28]. According to Beun et al.[29], a mechanism for the formation of aerobic granular sludge in an aerobic reactor without the presence of a carrier material is proposed via a series of microscopic observation. The proposed mechanism is schematically illustrated in Figure 2.

![Figure 2: Proposed mechanism of granulation after the start-up of SBR with a short settling time [29]](image)

At the beginning stage of the biogranulation, fungi and filamentous bacteria easily form mycelial pellets which settle very well and can be retained in the reactor. Bacteria do not possess this special property and will be washed out almost completely. Therefore, during the start-up period, the biomass in the reactor will consist mainly of filamentous mycelial pellets. As the granulation proceed within the reactor, due to the shear force in the reactor, detachment of the filaments on the surface of the pellets takes place and the pellets become more compact. The pellets grow out to a diameter of 5±6 mm and then undergo a lysis process due to the oxygen limitation in the inner part of the pellet. The mycelial pellets seem to function as an immobilization matrix in which the bacteria can grow out to colonies. When the mycelial pellets fall apart due to lysis of the inner part of the pellets, the bacterial colonies can maintain themselves because now they were large enough to
settle. These microcolonies further grow out to become denser granular sludge, leading eventually to a bacterial dominated population in the reactor as the granulation proceed [29-30].

**Advantages:**
The aerobic granules were known to exhibit attributes of compact, regular, smooth and nearly round in shape; excellent settle ability; dense and strong microbial structure; high biomass retention; ability to withstand high organic loading rate or shock loadings; endurance to starvation; tolerance to toxicity and simultaneous COD, nitrogen and phosphate removal [25, 31-32]. Bio-augmentation of specific bacteria strains which were able to degrade a target recalcitrant compound was also possible as these bacteria can be introduced as inoculum during the granulation period. For example, the AGS was successfully cultivated in a SBR treating high strength pyridine wastewater, using a single bacterial strain *Rhizobium sp.* NJUST18 as the inoculum [33]. The degradation of 2-fluorophenol with the AGS in a SBR also achievable with inoculation of *Rhodococcus sp.* FP1 [19].

**Application in wastewater treatment:**
Due to their unique attributes, the aerobic granulation technology was recently developed for treating a variety of high strength raw wastewater. Table 2 summarised the application of the AGS technology in treating either synthetic or raw wastewater and their overall treatment efficiencies.

**Table 2:** The aerobic bioganulation technology applied for a broad diversity of synthetic and raw industrial wastewater

<table>
<thead>
<tr>
<th>Type of wastewater</th>
<th>Treatment efficiencies</th>
<th>Description</th>
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<tr>
<td>Pyridine [33]</td>
<td>Complete degradation of pyridine.</td>
<td>120 days of SBR operation with maximum concentration of pyridine up to 4000 mg/L. Bioaugmentation of specific degrader (<em>Rhizobium sp.</em> NJUST18).</td>
</tr>
<tr>
<td>2-fluorophenol (2-FP)[34]</td>
<td>Complete degradation of 2-fluorophenol.</td>
<td>444 days of SBR operation with 0.44 mM of 2-FP as fed. Bioaugmentation of specific degrader (<em>Rhodococcus sp.</em> FP).</td>
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<td>Palm oil mill effluent [35]</td>
<td>Chemical oxygen demand (COD) removal efficiencies between 85% and 95%; ammonia removal efficiencies of between 89.3% and 97.6%; and maximum colour removal of 66%.</td>
<td>60 days of SBR operation with organic loading rate (OLR) of 2.5 kg CODm⁻³/day.</td>
</tr>
<tr>
<td>Textile wastewater (synthetic) [36]</td>
<td>Maximum COD, ammonia and colour removal of 94%, 95% and 62%, respectively.</td>
<td>70 days of SBR operation with COD concentration of 1250 mg/L.</td>
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</table>
Maximum removal efficiencies of COD and colour removal reached 46% and 61%, respectively. 112 days of SBR operation with maximum concentration of COD up to 4000 mg/L. Bioaugmentation of a specific microbial consortium (*Bacillus pumilus* ZK1, *Bacillus cereus* ZK2, *Brevibacillus panacihumi* ZB1, and *Lysinibacillus fusiformis* ZB2).

Maximum removal efficiencies of MB and COD reached 56% and 93%, respectively. 173 days of SBR operation with mg/L of MB and 500 mg/L of COD as fed.

Maximum removal efficiencies of 2,4-DCP and COD reached 94% and 95%, respectively. 50 days of SBR operation with 50-80 mg/L of 2,4-DCP and 900 mg/L of COD as fed.

Maximum removal efficiencies of COD, ammonia and phosphate reached 95.1%, 99.3% and 83.5%, respectively. 120 days of SBR operation with COD concentration of 1250 mg/L.

Maximum removal efficiencies of COD, nitrogen and phosphate reached 74%, 73% and 70%, respectively. 80 days of SBR operation with organic loading rate (OLR) of 9 kg CODm$^{-3}$/day.

Maximum volumetric conversion rates for nitrogen and phosphorus were 0.17 and 0.24 kg/m$^3$/d respectively. The energy usage was 13.9 kWh which is 58-63% lower than the average conventional activated sludge. Full-scale AGS technology implemented for industrial and municipal wastewater treatment under the trade name Nereda®.

**Limitations:**
Although the aerobic granulation technology has been successfully applied for the treatment of lots of different types of wastewater, however most of the research achievements of AGS were from bench-scale SBR, while the volume of the reactors was usually small (0.5-4 L) with limited processing capacity and their operational conditions were strictly controlled [42]. Apparently, the results of those researches had only theoretical guiding implication for practical engineering applications, and therefore AGS technology need to be testified by vast pilot projects treating different types of raw wastewater. However, the researches in this field were scarce, neither at local or abroad [43]. Furthermore, according to previous researches, AGS was easily unstable, slow growing and disintegrated in long-term operational reactors, which were the biggest bottleneck of AGS for engineering [32]. The formation and maintenance of AGS in SBR required relatively high cost associated with aeration, which was the main defect and limit for the scaling up of AGS reactors towards full scale industrial level [44]. A full scale treatment plant for domestic sewage under the trade name Nereda® has been fully set-up at Netherlands with the implementation of
AGS technology, with the treatment efficiencies and overall maintenance cost achieved were very promising [41]. However, this success can only be accomplished with over a decade of continuous researches. The findings were also cannot be implemented for other types of raw industrial wastewater, simply due to the difference in the chemical properties of the wastewater and operational conditions of the AGS reactors.

**Microbial Fuel Cell (MFC) Technology**

Recently, the application of MFC technology for the treatment of wastewater with the generation of electricity has been widely reported. MFC is a biochemical device that uses bacteria as a biocatalyst to convert chemical energy present in organic matter (e.g. glucose) into electricity [45-46]. Basically, MFC consists of an anaerobic anode chamber, a cathode chamber and a proton exchange membrane (PEM) or salt bridge which separates both chambers and only permits the transfer of proton (H⁺) from the anode chamber to the cathode chamber. Bacteria gain energy by transferring electrons from its central metabolic system to the anode, which acts as the final electron acceptor in MFC. The electron is then conducted across an external circuit to the cathode where they combine with oxygen and H⁺ to form water. Currently, both mixed and pure cultures of bacteria have been utilised in MFC to generate electricity [45, 47-50]. The transfer of electron from bacteria to the anode, known as the extracellular electron transfer mechanism in MFC can be achieved in three different pathway; (1) direct outer membrane c-type cytochrome transfer, (2) exploitation of electron mediators that are either externally added or produced by the microorganisms themselves, (3) through electrically conductive pili [8-10].

**Advantages:**

MFC offers several advantages over other energy generating technology from organic matter. These advantages according to Rabaey and Verstraete [54] include, high energy conversion efficiency due to direct conversion of chemical energy within substrate to electricity, efficient operation at ambient and low temperatures and lack of gas treatment since gases released are rich in CO₂ which have no useful energy content. In addition, aeration is not required since the cathode is aerated passively [55], thus reducing the cost of operation.

**Application in wastewater treatment:**

Most wastewater contain considerable amount of organic compound such as acetate and butyrate that can be utilised as the substrate in MFC to produce electricity. In light of this, different types of wastewater have been successfully utilised for simultaneous treatment and generation of electricity. Instead of removing these contaminants from wastewater through physical or chemical method, MFC provides an alternative method for wastewater treatment by harnessing the chemical energy within the biodegradable compounds using bacteria, subsequently generating a sustainable and clean electricity. Among the substrates that were successfully used to remove pollutant and produced energy using MFC includes: paper recycling
wastewater [56], domestic wastewater [56-57], food processing wastewater [58], starch processing wastewater [59], chocolate industry wastewater [60], mustard tuber wastewater [61] and textile wastewater containing azo dyes [62-64].

The highly polluted palm oil mill effluent (POME) which is characterised by high level of BOD and COD makes it a suitable substrate in MFC. Previous study has shown that a maximum power generation of 45 mW/m$^2$ was achieved using a double-chambered MFC using POME as substrate with 45% of COD removal in 15 days [65]. In another study, a double-chambered MFC successfully generated electricity up to 622 mW/m$^2$ using POME while MFC using artificial wastewater containing acetate produced 3004 mW/m$^2$ [66]. MFC system has also been integrated into other established treatment system to enhance the treatment process. Using an integrated upflow membrane-less microbial fuel cell (UML-MFC) system, most of the pollutants in POME were treated more effectively than the conventional anaerobic digestion system [67]. The result of their study showed that COD and ammoniacal nitrogen removal were above 96.5% and 93.6% respectively. Brewery wastewater is also one of the ideal substrates used in MFC for electricity generation and wastewater treatment due to its low concentration of inhibitory substances and high organic matter content [68]. The carbohydrate content is also high while the ammonium nitrogen is low. These features make it a very good candidate in MFC. It was found to be feasible and stable to produce electricity by [69] in which the COD removal obtained was kept between 40-43%. The result also showed that the highest power density obtained was around 264 mW/m$^2$ with open-circuit voltage up to 0.578 V. Just recently, a 90-liter stackable pilot MFC was developed and successfully generated electricity and at the same time treated the brewery wastewater [70]. The system was stacked by 5 easily-stackable modules, and operated in an energy self-sufficient manner for more than 6 months. The removal efficiencies of COD and suspended solid under two different influent strengths (diluted wastewater, stage 1; raw wastewater, stage 2) were 84.7% and 81.7% at stage 1, 87.6% and 86.3% at stage 2. Remarkably, the system generated sufficient energy (0.056 kWh/m$^3$ at stage 1, 0.097 kWh/m$^3$ at stage 2) to power the pumping system (0.027 kWh/m$^3$ at both stages), and the net electrical energy harvested were 0.021 kWh/m$^3$ and 0.034 kWh/m$^3$. The outcome of the study provides a clear indication that MFC technology is not far from its real application and could be applied very soon.

Limitations:

Considering the power output and treatment efficiency of MFC technology, the system is still not fully developed and ready for real application. The major drawback of utilising MFC is the low power density in MFC that hinders the scaling up of the system. Thus, research in advancing materials and architectures that are economically feasible and produce high power densities [71] has become a focal point in MFC research. Membrane fouling is a common problem in MFC setup with membrane which occurs frequently especially in treating wastewater containing high quantity of suspended solid. These membranes may require continues replacement, subsequently increasing the cost of operation. This has limited the commercial application of MFC for wastewater treatment. Hence, most of the experiments carried out are still on the
laboratory scale. High internal resistance is another factor that hinders the power density in MFC [72]. The factors connected to reactor configuration which are collectively refer to as internal resistance or over-potential could limit the power density of the MFC. It is therefore necessary during scale up process to reduce this internal resistance by optimising the electrolyte and the reactor configuration.

**Conclusions**
This paper is a review of the application of biofilm technology, aerobic granulation and microbial fuel cell for the treatment of wastewater. The treatment performances in terms of their advantages, applications and limitations have been discussed thoroughly. The ultimate goal of the wastewater treatment is the protection of the environment in a manner commensurate with public health and socio-economic concerns. Understanding the nature of wastewater is fundamental to design an appropriate treatment technology in order to ensure the safety, efficacy and the quality of the treated wastewater. Further, improved public education to ensure awareness of the technology and its benefits, both environmental and economic, is recommended.

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**References**


