A review of the operating parameters on the microbial fuel cell for wastewater treatment and electricity generation

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ABSTRACT

Environmental and economic considerations suggest a more efficient and comprehensive use of biomass for bioenergy production. One of the most attractive technologies is the microbial fuel cell using the catabolic activity of microorganisms to generate electricity from organic matter. The microbial fuel cell (MFC) has operational benefits and higher performance than current technologies for producing energy from organic materials because it converts electricity from the substrate directly (at ambient temperature). However, MFCs are still not suitable for high energy demand due to practical limitations. The overall performance of an MFC depends on the electrode material, the reactor design, the operating parameters, substrates, and microorganisms. Furthermore, the optimization of the parameters will lead to the commercial development of this technology in the near future. The simultaneous effect of the parameters on each other (intensifier or attenuator) has also been investigated. The investigated parameters in this study include temperature, pH, flow rate and hydraulic retention time, mode, external resistance, and initial concentration.

Key words: bioenergy, microbial fuel cell, review, wastewater treatment

HIGHLIGHTS

• We discuss about operating parameters that affect MFC in this review.
• Knowing different parameters.
• Simultaneous effect of parameters on each other.
• The concentration effect and the impact of nitrogen presence.
• The flexibility of the system.
• Optimize and design it better.

INTRODUCTION

In recent decades, population growth, urban sprawl, industrial and agricultural production, and the consumption of various chemicals, on the one hand lead to the production of sewage and environmental pollution (Yang et al. 2013; Thung et al. 2015; Raji & Mirbagheri 2021). On the other hand, they lead to fossil fuels consumption and its generated pollutants (Ter Heijne et al. 2007; Wu et al. 2015).

Lack of fossil fuel resources and the effects of global warming have led to a focus on biomass as a sustainable source of energy production (Demirbas et al. 2009). Unlike fossil fuels, biomass is renewable and has a closed carbon cycle (Orecchini & Bocci 2007).

One of the most attractive technologies for bioenergy production is the microbial fuel cell (MFC), which is a good option for organic wastewater treatment and the co-production of energy (Gil et al. 2003). MFCs are bioreactors that use microorganisms as catalysts to oxidize organic compounds and inorganic compounds and produce currents (Qian & Morse 2011). A wide range of substrates, from pure compounds (Rabaey & Verstraete 2005) (such as acetate (He et al. 2008), glucose (Cercado-Quezada et al. 2010), butyrate (Rabaey & Verstraete 2005) to complex mixtures (such as municipal wastewater (Feng et al. 2008), brewery effluent (Feng et al. 2008) and starch production (Kim et al. 2004; Liu et al. 2009) and leachate (Habermann & Pommer 1991; Zhang et al. 2008) have been studied in MFCs so far (Rodrigo et al. 2007; Pant et al. 2010). Researchers have tried to investigate substrates in a wide range of different types of artificial and natural effluents. Substrate...
type widely affects the accumulation of microorganisms, their mortality, and power generation rate (Jung & Regan 2007; Kim et al. 2007).

However, MFC has not yet been used for wastewater treatment systems because MFC is a new technology and needs more time to be explored. Another reason is that the power generated is low compared to its competitors such as the methane production anaerobic digester (Pham et al. 2006). Recent research shows that MFC is a practical plan among other options for sustainable bioenergy production in the near future. Increasing the efficiency and decreasing the price of MFC helps to commercialize it; to achieve this, knowing the parameters affecting the MFC performance and optimizing them can be very helpful (Bifinger et al. 2007). MFC performance depends on reactor type (Choi & Chae 2013; Mukherjee et al. 2013), configuration (Du et al. 2007), wastewater type (Liu et al. 2011a; Kim et al. 2016), electrode material and surface (Sangeetha & Muthukumar 2013; Zhu et al. 2013; Santoro et al. 2014; Zheng et al. 2016), anodic potential (Wang et al. 2009; Wei et al. 2010), microbial diversity (Mukherjee et al. 2013). Moreover, it depends on operating parameters such as temperature (Patil et al. 2010; Tee et al. 2017), external resistance, pH (Puig et al. 2010), time (Arya et al. 2016; D’Angelo et al. 2017), concentration (Pant et al. 2018), ionic strength (Logan et al. 2006; Aelterman et al. 2008; Jadhav & Ghangrekar 2009).

The aim of this study is to know the parameters affecting MFC and their impact by reviewing previous research in order to optimize the system in terms of cost and efficiency.

**Definition of microbial fuel cell**

MFC is a tool that uses the catabolic activity of microorganisms to generate electricity from organic matter (Watanabe 2008). At the anode, organic matter is oxidized by electrochemically active microorganisms and electrons being released. The generated electrons are then transferred to the cathode via an external circuit and electricity is generated (Frijters et al. 2006; Solanki et al. 2013). Numerous models have been designed for MFC, but they can be divided into two categories, dual-chamber, and single-chamber (Figures 1 and 2) (Solanki et al. 2013).

Dual-chambers include an anaerobic anode chamber and aerobic cathode chamber, which are separated by a proton exchange membrane (PEM) (Xu et al. 2012; Parkash 2015). The substrate is oxidized as a fuel by microorganisms in the anaerobic chamber in which the anode electrode is located, and electrons and protons are released (Venkata Mohan et al. 2008b; Oh et al. 2010). Protons transfer to the cathode chamber through the proton exchange membrane, protons and electrons react with oxygen to form water in the cathode chamber (Rabaey & Keller 2008). For instance, the following reactions show the oxidation of acetate at the anode and the reduction of oxygen at the cathode (Scott & Yu 2015).

\[
\text{CH}_3\text{COO}^- + 2\text{H}_2\text{O} \leftrightarrow \text{CO}_2 + 7\text{H}^+ + 8e^- \\
\text{O}_2 + 4e^- + 4\text{H}^+ \rightarrow 2\text{H}_2\text{O}
\]

**Figure 1** | Schematic diagram of two-chambered MFC.
In a single-chamber system, as in Figure 2, the cathode and PEM chambers have been removed; therefore, it has a simpler design and more affordable price (Liu & Logan 2004; Sun et al. 2009). The cathode is exposed to air on one side and water on the other side (inside) (Wang et al. 2008). Anodic reactions are similar to a dual-chamber system and oxygen in the air can directly react at the electrode (Hou et al. 2011; Sun et al. 2012).

Key parameters influencing the MFC

In addition to the electrode specifications and the reactor configuration, the MFC performance also depends on the characteristics of the wastewater and the various operating parameters such as temperature, pH, and organic loading rate (Oliveira et al. 2013). In this section, the effect of pH, temperature, input concentration, hydraulic retention time (HRT), flow, external resistance and operating mode (batch and continuity) are investigated.

pH

The pH of the anodic part is one of the important factors in the efficiency of MFCs that can affect the metabolic activity of microorganisms (He et al. 2008). Furthermore, the mechanism of electron and proton (H+) production is affected by pH (Behera & Ghangrekar 2009; Yuan et al. 2011).

MFC performance is strongly influenced by pH. Increasing the pH has a positive effect on the current density (Table 1) and coulombic efficiency because the electron transfer is easier (Behera & Ghangrekar 2009). Moreover, it has a beneficial impact on COD removal (Behera et al. 2010). However, in some studies, lowering the pH leads to increasing the organic matter removal efficiency due to the activity of methane-producing microorganisms (Behera & Ghangrekar 2009). Based on the studies, optimum pH is about 7 and 8, as the microbial activity is more suited (Behera et al. 2010). Both lower and higher pH has an adverse effect on dual-chamber MFCs (Gil et al. 2003; Ren et al. 2007; He et al. 2008). As seen in Table 1, higher pH has a positive effect on single-chamber MFCs.

Besides, the metabolic activity of bacteria change the pH (He et al. 2008), which is strongly dependent on the initial pH. If the initial pH is less than 8, after a day or two the output pH increases (Zhao et al. 2006), because proton exchange through the membrane has been slower than the proton production rate. So protons are limited to reactions at the cathode where oxygen as an oxidant is present. The result is the accumulation of protons in the anode leading to a drop in pH (Cheng & Liu 2006). If the initial pH is above 8, the pH decreases because metabolic activities produce weak acid and the activity rate of microorganisms is higher at this pH (Newman 1994; He et al. 2008).
Temperature

Temperature as an important parameter in the process of decomposition and anaerobic digestion is considered (Adekunle & Okolie 2015). Most microbial decomposition processes operate in the mesophilic temperature range (Gavala et al. 2003). The optimum temperature for mesophilic microorganisms in the range of 35 to 40 °C is known (Bohn et al. 2007). When the temperature falls outside this range, the activity of microorganisms gradually decreases.

Based on the performance of MFCs, production of electricity from wastewater treatment is improved primarily in the higher temperature range (Ahn & Logan 2010). Although MFCs perform better at higher temperatures, they are not as sensitive as conventional anaerobic systems in the relatively low-temperature range of 4 and 15 °C and it has also reasonable efficiency compared to other systems (Bohn et al. 2007). So this is one of the advantages of the MFC as far as it can be an appropriate choice for the cold regions with a low flow rate of urban wastewater (Larrosa-Guerrero et al. 2010; Krieg et al. 2019). In MFC, electroactive anodic consortia are produced, which are able to remove COD and generate electricity even at 4 °C (Larrosa-Guerrero et al. 2010). Li et al. examined the power generation of the MFC system in the temperature range of 10 to 55 °C. According to the results, increasing the temperature from 10 to 33 °C led to an increase in current density and then it started to decrease, and there was no constant power from 43 to 55 °C (Li et al. 2013a). Similar results were observed in another study; however, the optimal temperature was 45 °C (Liu et al. 2011b).

Batch or continuous

MFC systems are examined in three modes: batch, fed-batch, and continuous (Logan et al. 2006). Many studies have been investigated in batch mode, but batch systems have many disadvantages such as reduced substrate due to limited food and toxic by-products (Peppas 1986). Moreover, it leads to a sharp decline in MFC power generation (Choudhury et al. 2020). The fed-batch method partially solves this problem and prevents food shortages and power loss (Choudhury et al. 2021). Most studies have been investigated in the fed-batch mode which whenever a power loss is observed, the influent is renewed (Hiegemann et al. 2019). However, power generation is more suitable for practical applications in continuous mode (Chung & Okabe 2009), because batch systems are applied less for wastewater plants. Overall, continuous system operation benefits are including the composition of the medium, secondary metabolite production, growth kinetics, kinetic constants, easier operation, and more reliable and repeatable results (Dunnill 1987). The purpose of continuous MFC research is to evaluate and improve the purification capability (Rabaey et al. 2005; Venkata Mohan et al. 2008a; Wen et al. 2009) and the highest COD removal efficiency is about 70 to 90% (Feng et al. 2010).

In terms of performance, batch and continuous achieve almost similar results; however, continuous systems generate less electricity in low hydraulic retention time (HRT) since the chemical oxygen demand (COD) concentration decreases during
Flow rate and hydraulic retention time

HRT is a significant parameter in wastewater treatment that directly affects design (flow rate and construction), operation, and cost (Akman et al. 2013; Sobieszuk et al. 2017). In fact, the longer the time, the higher the cost, but time affects the removal rate and power generation (Akman et al. 2013). To become economical and practical, the retention time of MFC must be close to the conventional processes (Kim et al. 2015). Theoretically, HRT is dependent on the flow rate and volume and is inversely related to flow (Xu et al. 2015).

The increase in HRT increases the efficiency of COD and coulombic efficiency (CE) (You et al. 2006; Haavisto et al. 2017) because the volumetric organic loading rate rises (Sobieszuk et al. 2017). Furthermore, the increasing time leads to increased pollutant removal efficiency such as total nitrogen (TN), ammonium, nitrate, COD, pharmaceutical products (Li et al. 2013b; Ma et al. 2016; Chang et al. 2018).

Retention time has a greater impact on continuous systems (Sobieszuk et al. 2017). The increase in HRT from 8 to 16 hours results in reducing the voltage from 0.21 to 0.15 hours (Ahn & Logan 2012). For the average COD concentration in the reactor is decreased (Ma et al. 2016). The higher the HRT, the greater the microbial diversity (HaiLiang et al. 2018). It is worth mentioning that retention time and flow rate are inversely related to each other. Flow has a dual effect because it affects both mass movements and biofilm stabilization (Jia et al. 2016). If the influent flow rate increases, actually the time decreases, leading to an increase in dilution rate and a decrease in generated electricity (You et al. 2018).

Since HRT is directly related to the removal efficiency and inversely related to the current density, the optimum time must be found in such a way that both give acceptable results. Initial culture conditions greatly affect the optimal retention time (Mateo et al. 2017). Hence, considering different residual times is more due to diverse microbial communities than different configurations. Since MFCs are dynamic systems, the optimized HRT for an MFC can vary over time (Ieropoulos et al. 2010; Sobieszuk et al. 2017). The optimal time in some studies has been obtained as equal to 15.5 hours (Li et al. 2008), 20 hours (Huang et al. 2008), 11.3 hours (Liu et al. 2008), and 24 hours (Haavisto et al. 2017).

External resistance

Although the bacteria involved in power generation can overcome the resistance caused by the system, system losses can be minimized by selecting the desired external resistance, and also system performance will be optimized (Clauwaert et al. 2008). If the external resistance is optimal, the output power and the coulombic efficiency increase, and the methane production decrease (Pinto et al. 2010). Through the external resistance, the current rate and cell voltage can be controlled (Can et al. 2014).

In a microbial fuel cell, like any other power source, the goal is to maximize output power. Voltage decreases by decreasing the applied external resistance, but current density increases. Therefore, the suitable voltage loss must be obtained when the current increases to achieve maximum power density. Moreover, the maximum power density is achieved when the internal and external resistances are equal. The external resistance producing the maximum power is accessible using the polarization curve (Figure 3). The optimum points and internal resistance are calculated from polarization curves using the power density peak method (Davis 1967; Logan & Regan 2006; Aelterman et al. 2008; Logan 2008; Manohar et al. 2008; Woodward et al. 2010). The internal resistance may change under different conditions such as pH, temperature, and wastewater characteristics. Naturally, the optimal external resistance also changes (Pinto et al. 2010; Zhang & Liu 2010; Corbella & Puigagut 2018).

External resistance is one of the most important parameters for the commercialization of MFC. In general, MFC performance, both removal efficiency and output current, increases with decreasing external resistance (Katuri et al. 2011; Buitrón et al. 2017). Lee and et al. showed that at lower external resistance, the maximum power was higher (Liu et al. 2005). As the resistance decreased from 50 to 25 and to 10.5 Ω, the current density and power increased (Aelterman et al. 2008). The COD removal efficiency is high in MFC, but the efficiency increases slightly with decreasing resistance (Ahn & Logan 2012).

External resistance is one of the most common parameters affecting MFC, which influences the start-up time directly (Molognoni et al. 2014). Increasing resistance reduces start-up time. For instance, in one study, an external resistance increase...
from 10 to 1,000 Ω led to reducing startup time from 3 days to 0.6 days. This means that the growth of microorganisms occurs faster at higher resistances (Zhang et al. 2017; Suzuki et al. 2018). However, after starting the system, the lower the resistance, the greater the output current (Katuri et al. 2011). It is worth mentioning that very low resistances of up to 10 make the start-up process difficult since the growth and evolution rate of microorganisms decreases; moreover, low external resistance causes thin and compact biofilm (Zhang et al. 2017), and also biomass yield increases in higher external resistance (Katuri et al. 2011). Therefore, first, it is better to start up MFC with high resistance then gradually change to low resistance in order to reach a higher current generation (Ahn & Logan 2012). However, in Buitrón’s research, changing the resistance from the adaptation resistance leads to a reduction in efficiency and power production, and this is one of the factors in the difference in cell function (Buitrón & Moreno-andrade 2014).

Microbial and metabolic diversity also change with changing resistance (Aelterman et al. 2008; Lyon et al. 2010; Suzuki et al. 2018). Because the anode biofilm is dependent on external resistance, and the reason for changing the microbial population is the change in external resistance (Lyon et al. 2010; Mclean et al. 2010). Based on research, low external resistance increases the evolution rate of energy gain, energy output, active biomass, and maximum power density during startup but reduces voltage evolution rate of the population (Zhang et al. 2017).

Initial concentration
COD
A gentle substrate increase in the anolyte (the portion of an electrolyte near an anode, especially in a cell in which the cathode and anode are in separate compartments), through fed-batch or flow, can increase or decrease the power produced by the system (Rabaey et al. 2003; Borole et al. 2011; Xu et al. 2017).

COD concentration has a significant effect on electricity generation, and its increase leads to an increase in electricity production but has little effect on removal efficiency (He et al. 2016). About 25% of the removed COD is used to generate electricity, so the remaining COD is removed by the anaerobic process (Rodrigo et al. 2007). Moon et al. showed that an increase in COD concentration from 100 to 400 mg/L increased the current from 2.2 to 6.8 mA, and Colombian yields fell. Moreover, high flow leads to transferring large amounts of fuel from the anode to the cathode, which is reduced in the aerobic chamber by aerobic bacteria, and so the coulombic efficiency is reduced (Moon et al. 2005).

Asensio et al. examined different concentrations of acetate (COD from 500 to 20,000 mg/L). According to the results, increasing COD from 500 to 5,000 mg/L linearly causes increasing power generation, but the further increase in COD reduces efficiency. COD removal efficiency also increased to a peak in 1,000 mg/L and then slightly decreases (Asensio et al. 2015).

![Figure 3 | Polarization curve.](https://iwaponline.com/wst/article-pdf/84/6/1309/942174/wst084061309.pdf)
et al. 2016). Extremely low COD concentrations are not suitable at all because the power production is reduced. That’s why the power production of the last MFC chamber will be minimum in stack mode (Ahn & Logan 2013; Ren et al. 2014). Stack requires high COD.

Nitrogen
The MFC system can remove COD and nitrate simultaneously (Al-Mamun et al. 2017). Since the anode chamber is anaerobic, MFC can reduce nitrate during denitrification (Lefebvre et al. 2008; Cai & Zheng 2013). Hence, this system can be a good pre-treatment for the denitrification process to reduce nitrate (Nguyen et al. 2016).

Before denitrification, nitrite is converted to nitrate at the anode chamber and releases electrons (Faraghi & Ebrahimi 2012). Despite producing electrons, nitrite cannot generate electricity exclusively but can be helpful along with COD. Low nitrite concentration, up to 60 mg/L, increases power generation, but further increase has an adverse effect because it inhibits the activity of anodic bacteria (Wang et al. 2020).

The presence of cations such as ammonium (NH$_4^+$), calcium (Ca$^{2+}$), magnesium (Mg$^{2+}$), sodium (Na$^+$), and potassium (K$^+$) in the substrate leads to an increase in pH in the cathode chamber since they pass through the proton exchange membrane (Rozendal et al. 2006). Therefore, ammonium also passes through the membrane and enters the cathode chamber, and finally escapes in the form of ammonia (Jung et al. 2008). Ammonium passing through the membrane can be harmful, but according to a study by Kuntke et al., increasing ammonium (from 0.07 to 4 g) does not affect efficiency, and it is non-toxic (Kuntke et al. 2011).

Wang et al. investigated the ratio of COD to nitrogen (COD/TN) on nitrogen removal in MFC. When the ratio decreases, the nitrogen effluent concentration reduces (Wang et al. 2019).

The effect interaction of parameters
The purpose of this section is to investigate the simultaneous and interaction effects of the parameters together to select the parameters correctly for optimization and also reduce the adverse effects of parameters. Parameters can intensify and reduce each other or eliminate the effect of a parameter. Furthermore, the impact of each parameter on efficiency is different, and one parameter’s effect may be negligible compared to other parameters. Some articles that have examined the simultaneous and interaction effects of the parameters are listed in Table 2. However, the number of papers that have investigated this issue is very low. Therefore, it is suggested that more attention should be paid to the simultaneous effect of parameters in future studies using the design of experiments (DoE). To identify and reduce the number of experiments, different DoE methods such as full factorial, fractional factorial, Taguchi, and response surface methodology (RSM) can be applied. (Antony 2006; Raissi & Farsani 2009; Chen et al. 2015; Mirbagheri et al. 2017). Additionally, for better analysis of the results, statistical methods like ANOVA and non-statistical analysis techniques such as neural networks can be used (Del Vecchio 1998; Jensen 2008; Anderson & Whitcomb 2016; Boudaghpour & Malekmohammadi 2020). It is worth mentioning that the Design-expert software can resolve some needs of experimental chemists, from screening to modeling and optimization (Alben 2002). Knowing the effect of each parameter and their simultaneous interaction will exceedingly help in the optimal design in terms of efficiency and cost. As seen in the table below, many parameters do not interact with each other. However, if both are directly related to efficiency, they increase efficiency and vice versa.

CONCLUSION
The microbial fuel cell is a nascent technology that has many unknown aspects. This system has not been installed on an industrial and large scale yet but commercializing MFC is not unattainable with optimization and upgrades. It seems that the maximum productivity and efficiency are highly dependent on start-up and operation parameters, and considering them can help achieve an optimal microbial fuel cell.

MFC performance is strongly influenced by pH, and slightly basic pH, about 8, is very suitable. The temperature changes have little effect on efficiency, but higher temperatures are better. Increasing the HRT leads to an increase in the power generation of continuous systems, and its effect on batch systems is reversed but increasing the HRT always leads to an increase in COD removal efficiency. MFC performance, both removal efficiency and power production, increases with decreasing external resistance, but it increases startup time. COD concentration has the greatest impact on power generation and has a direct relationship. However, it has little effect on COD removal efficiency. Therefore, in the stack mode, the concentration...
### Table 2 | Simultaneous effect of parameters

<table>
<thead>
<tr>
<th>Parameter 1 = HRT Parameter 2 = External Resistance</th>
<th>Condition (reactor/operational specifications)</th>
<th>Comments</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter 1 = pH Parameter 2 = External Resistance Parameter 3 = Distance between electrodes Parameter 4 = pH</td>
<td>- Single chamber - Multi brush anode - Temperature = 30 °C - Operation mode = continuous</td>
<td>- The impact of resistance is insignificant at shorter HRTs - The impact of HRT is greater than the resistance</td>
<td>Ahn &amp; Logan (2012)</td>
</tr>
<tr>
<td>Parameter 1 = pH Parameter 2 = External Resistance Parameter 3 = Distance between electrodes Parameter 4 = pH</td>
<td>- Sediment microbial fuel cell - Electrode = graphite plate - Temperature = 29–30 °C - COD concentration = 170–180 mg/litre</td>
<td>- Resistance and pH have an intensifying effect on COD removal and output current density - Reducing the pH leads to an increase in COD removal efficiency, an issue that is greater at lower resistances. - Increasing the electrode distance leads to an increase in removal efficiency, which intensifies at low pHs. - Decreased resistance leads to an increase in the power density and the pH changes have little effect on it. - Reducing the electrode distance increases the power density, and decreasing resistance intensifies its effect. - pH among all parameters is more effective in the removal of COD. - The electrode distance parameter is more effective on the current density than all other parameters, and in the next step are the resistance and pH.</td>
<td>Sajana et al. (2014)</td>
</tr>
<tr>
<td>Parameter 1 = pH Parameter 2 = Concentration Parameter 3 = HRT Parameter 4 = inoculum composition (Pure &amp; Co-Cultured)</td>
<td>- Dubbed-chamber - Electrode = Carbon felt - PEM = Nafion 117 - Room temperature</td>
<td>- Generally, the interaction between the parameters of initial COD, HRT, and pH is low. However, the effect of inoculum composition on HRT, pH, and initial COD is significant. HRT, for example, greatly increases the effect of inoculum composition.</td>
<td>Islam et al. (2018)</td>
</tr>
<tr>
<td>Parameter 1 = pH Parameter 2 = Temperature Parameter 3 = Concentration</td>
<td>- Mediator-less single-chamber - Cathode = Wet proofed carbon cloth and PEM - Domestic wastewaters - External resistance = 150 Ω - pH = 6.5–7 - Temperature = 25 °C - Operation mode = Batch - Pentachlorophenol (PCP)-glucose concentration = 50–1,500 mg/L</td>
<td>- pH and temperature do not interact with each other, but increase in both of them drastically increases the power density production and coulombic efficiency. In addition, the slope of the pH graph is steeper, so the pH parameter is more efficient. - pH and concentration do not have a reciprocal effect on each other in the power production, but at lower pHs, there is a greater effect of concentration on Coulombic efficiency. - Increasing the concentration strongly affects the power density production, which is more noticeable at low temperatures. However, the interaction between two parameters does not affect coulombic efficiency.</td>
<td>Alshehri (2015)</td>
</tr>
<tr>
<td>Parameter 1 = pH Parameter 2 = Internal Resistance</td>
<td>- Dual chambered mediator-less</td>
<td>- When pH is lower, the internal resistance increases</td>
<td>Behera &amp; Ghangrekar (2009)</td>
</tr>
</tbody>
</table>
must be very high to for enough COD to reach the last cells. It is worth mentioning that the presence of nitrogen does not cause any problems in MFC except in high nitrate amounts and it is well removed.

**DATA AVAILABILITY STATEMENT**

All relevant data are available in this paper or its supplement.

**REFERENCES**


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