Bio-electrochemical denitrification - A review

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Abstract
Discharge of nitrogen components into the environment can be cause of serious problems such as eutrophication of rivers and deterioration of water sources, as well as hazard for human and animal health. Ammonia (NH\(_3\)) and nitrate (NO\(_3^-\)) are the most problematic nitrogen compounds in water and wastewaters. Nitrification is common way to eliminate ammonia in municipal and industrial wastewater, which during this process ammonia oxides to nitrate. Therefore, nitrate removal from these types of wastewaters is an inevitable step in treatment. The biological nitrate removal is suitable method to deduct of nitrate from water and wastewater, which is a slow process. Therefore, in treatment plants, some abiotic methods have applied commonly. Nevertheless, these methods have indicated some drawbacks such as highly concentrated brine solution, which compels complexity for further treatment or disposal. Consequently, efforts have focused on speeding up microbial denitrification techniques, and different methods have investigated in last two decades. Among them bio–electrochemical, reactors (BERs) are equipped with immobilized autohydrogenotrophic microorganisms on cathode showed good efficiency for implementation of denitrification for any nitrate – contaminated water stream. Therefore, this article reviews the diversity of nitrate source, various designs, and aspects of BERs. In addition, trying to discuss the variation of pH, carbon source, electric current (EC) and hydraulic retention time (HRT) as some main effective parameters on denitrification rates, and different configurations of BERs.

\textbf{Keywords:} Nitrate, Denitrification, Bio-electrochemical reactor

1. Introduction
Ammonia (NH\(_3\)), ammonium (NH\(_4^+\)), nitrite ion (NO\(_2^-\)), and nitrate ion (NO\(_3^-\)) are the important form of nitrogen components in aqueous solution and soil [1]. These kinds of pollutants inter to environment from a variety of sources and are as contaminants, which have increased environmental problems in recent years. Therefore, effort to reduce emission and improve treatment methods for water and wastewater should be highlight as main public concern in future [2-4]. Among these nitrogen components NO\(_3^-\) is discharge into environment from various sources (natural cycle, and human activities), and know as worldwide health hazard. For example, in some part of the world such as USA, India, Japan, Saudi Arabia, China, UK and several parts of Europe people consume drinking water with high concentration of nitrate [5], and is increasingly becoming an important worldwide challenge. Nitrate in drinking water may reduce to nitrosamines in the stomach which is supposed to cause gastric cancer[6, 7]. In addition, drinking of water contain high concentration of nitrate can be cause of disease “blue baby syndrome” due to reduction of nitrate to nitrite inside the stomach of fetus, and nitrite reacts with the hemoglobin in blood and converts the hemoglobin into methemoglobin. This new compound does not carry oxygen to cell tissues [8].

Moreover, nitrate known as a carcinogenic compounds[9]. Therefore, to protect the consumers from adverse effects of high nitrate intake standards were determined for it in drinking water. The World Health Organization (WHO), US Environmental Protection Agency (EPA), and European Community establishes the limit Maximum contaminant level(MCL) for nitrates in drinking water at 50 mg NO\(_3^-\)/L, 12 mg/L N , and on 50 mg NO\(_3^-\)/L and 0.5 mg NO\(_3^-\)/L, respectively [10, 11]. Furthermore, different discharge standards were defined on base receiving environment, fresh water (10 and 30 mg NO\(_3^-\)-N/L ), seawater (50 mg NO\(_3^-\)-N/L ), and in sensitive areas discharge concentration is 10 and 15 mg TN/L [12].

In recent years, researchers have tried to improve remove of nitrogen component specially nitrate from water and wastewater, and in this way, they had some achievements. Therefore, goals of this review are mention on nitrate as health risk, explain the sources of nitrate briefly, and summarize various treatment methods of nitrate. Finally, focuses on mechanism of BERs, effective factors on efficiency of process, and performance of bio-electrochemical reactors.
2. Source of nitrate

The sources of nitrate divided to two subdivision “point sources” and “nonpoint sources”. The non-point agricultural source confirmed as one of the important nitrate sources to pollute groundwater due to extreme use of fertilizers[13]. Some other sources of nitrate in ground water and surface water are from uncontrolled land discharges of treated or raw domestic and industrial wastewaters, landfills [14], and animal wastes predominantly from animal farms [15]. Some industries wastewater such as dairy and swine are reported as wastewaters contain more than 200 mg NO$_3$-N/L[16]. Furthermore, some industries produce wastewater contain greater than 1000 mg NO$_3$-N/L such as producing explosives, fertilizer [7, 17, 18], cellophane, pectin, and metals finishing industries. Also, a number of activities like processing of radioactive metal products at nuclear weapons production plants and research labs produce wastewater consist high concentration of nitrate excess of 50000 mg NO$_3$ N/L [19].

3. Nitrate removal methods

Some compulsory regulations were presented for avoidance of environmental problems and prevention of health risks due to uncontrolled discharge of nitrate. To achieve discharge standards, reduction in the nutrients in wastewater below the discharge permit levels is required. Therefore, up to the present time, researches are carried out towards nitrogen components removal from industrial wastewaters, domestic wastewaters, water resources, aquaculture ponds, and aquaria. The most commonly used methods to remove nitrogen components from liquid waste specially ammonia are: chemical precipitation with magnesium ammonium phosphate, Ion exchange, bio-filtration, ammonia-stripping, electrolysis, break point chlorination, and electrochemical conversion [2, 4, 20, 21]. Moreover, The most familiar nitrate reduction consist two group “physicochemical” and “biological” treatment processes [19]. The common abiotic process consist ion exchange (IE), electro–dialysis (ED), reverse osmosis (RO) and activated carbon adsorption in combination with pH adjustment [14, 17, 22]. The biological nitrification/denitrification is only suitable for the removal of relatively low concentration of ammonia and nitrate due to the requirement of appropriate C/N ratio [2, 4, 20, 21]. Nitrate removal from drinking water and wastewater is difficult. Therefore, complementary techniques are required for obtaining a free nitrate stream in treatment plants [14, 17, 22].

Biological denitrification is suitable method to treat wastewater contain nitrate because nitrate can be transformed to harmless nitrogen gas with present of electron donor. However, biological remediation of wastewater with high concentration of nitrate with low chemical oxygen demand (COD) as carbon source and or internal electron donor, using an external source as electron donor is indispensable. Heterotrophic denitrification processes using methanol and acetate have been proposed in a suspended or attached growth reactor [11, 23]. Also, a wide interest towards some new methods such as metallic iron-aided abiotic nitrate reduction is recently reported by several researchers [23-25]. Ghabazi et al. [19] stated the disadvantages along with diverse abiotic techniques, which remove nitrate from water and generate a brine solution. But, denitrifying bacteria, which are ubiquitous in nature, are responsible for biological denitrification and use oxygen in nitrate as electron acceptor during their respiratory process instead of oxygen in anoxic condition and produce harmless gas “N$_2$” by reduction of nitrate/nitrite through four steps below [26].

\[
\begin{align*}
\text{NO}_2^- & \rightarrow \text{NO}_2^- \rightarrow \text{NO} \rightarrow \text{N}_2\text{O} \rightarrow \text{N}_2
\end{align*}
\] (1)

Denitrifying microorganisms belong to several taxonomic groups and physiological groups such as lithotrophs, organotrophs, and phototrophs. Denitrifying bacteria are common among the gram-negative alpha and beta classes of the Proteobacteria, such as Pseudomonas, Alcaligenes, Paracoccus, and Thiobacillus. Some gram-positive bacteria are denitrifying such as Bacillus, and a few halophilic Archaea like Halobacterium [27, 28].

Base on utilized food and energy sources, denitrifying bacteria are classified in another two major groups namely “heterotrophs” and “autotrophs” [1, 29]. Heterotrophs make use of organic carbon compounds as the carbon source [30], while autotrophic bacteria utilize inorganic carbons such as carbon dioxide or bicarbonate as the carbon source. In contrast to heterotrophs who use organic carbons as energy source, autotrophs make use of reduced inorganic compounds (e.g. ferrous iron, manganese, hydrogen sulfide) or molecular hydrogen (H$_2$) as electron sources to obtain energy [19, 30-32].

Heterotrophs are more preferable for denitrification of wastewaters due to availability of organic compounds in wastewaters. In addition, they apply for biological denitrification of drinking water. However, methods applying this kind microorganism are associated with some problematic consequences such as clogging in reactors, residual carbon sources and by-products, which typically impel a further costly post treatment [33-35]. On the other hand, autotrophic denitrifying bacteria offered conditions that are more favorable: they need inorganic compounds which are less expensive compared to organics, and their residuals in treated drinking water are harmless (for H$_2$) or less problematic (for reduced components) [35, 36]. Therefore, in recent years researchers have focused on denitrification by autohydrogenotrophic as autotrophic denitrifying, which is more promising than other autotrophic methods. Equation (2) shows reduction of nitrate to N$_2$ by hydrogenotrophic denitrification [19].

\[
2\text{NO}_2^- + 5\text{H}_2 \rightarrow \text{N}_2 + 4\text{H}_2\text{O} + 20\text{H}^-
\] (2)
3. Theory of denitrification by autohydrogenotrophic bacteria

To use this group of autodenitrifying bacteria preparing of hydrogen as electron donor play main role. Some researchers supply H₂ by sparging in reactor as initial method. But this method have some shortcoming such as costly provision of hydrogen gas, flammable and explosive mixtures of H₂ with air, transportation and storage problems [19, 26, 37]. Furthermore, It was mainly because of low solubility of H₂ in water (1.6 mg/L at 20 °C), which decline its availability and contact time for microbial reaction, and hence, it directly results in lower denitrification rates compared to heterotrophic denitrification [26, 35]. Therefore, in recent years researcher focus on present some new methods to solve sparging limitation, which now pathway, were investigated: chemical generation of H₂ and electrolysis of water [26, 38, 39]. Among them base on some weakness such as slow reaction rate and generation of unwanted by-products researchers confirmed electrolysis of water as a clean method to generate of hydrogen [38]. Consequently, exploit of electricity in denitrification process led to generation of new types of reactors named bio-electrochemical reactors (BERs) [17]. In this reactor according to table 1 take place some reactions during bio-electrochemical denitrification, which result is generation of H₂ on cathode by electrolysis of water according to Equations (3) and (4). Autohydrogenotrophs bacteria consume generated H₂ as electron donor and during reactions (5) to (8) transfer nitrate to N₂ [19, 37, 40, 41].

<table>
<thead>
<tr>
<th>Table 1. Bio-electrochemical denitrification reaction in BERs</th>
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<tbody>
<tr>
<td>Electrolysis of water in BERs:</td>
</tr>
<tr>
<td>5H₂O → 2.5H₂(g) + 10H⁺ + 10e⁻</td>
</tr>
<tr>
<td>10H₂O + 10e⁻ → 5H₂(g) + 10H⁺</td>
</tr>
<tr>
<td>Steps of nitrate reduction to nitrogen gas:</td>
</tr>
<tr>
<td>NO₃⁻ + H₂(g) → NO₂⁻ + H₂O</td>
</tr>
<tr>
<td>NO₂⁻ + 0.5H₂(g) + H⁺ → NO(g) + H₂O</td>
</tr>
<tr>
<td>2NO(g) + H₂ → N₂(g) + H₂O</td>
</tr>
<tr>
<td>N₂O(g) + H₂ → N₂(g) + H₂O</td>
</tr>
<tr>
<td>Net reaction</td>
</tr>
<tr>
<td>2NO₃⁻ + 6H₂O + 10e⁻ → N₂(g) + 12OH⁻</td>
</tr>
<tr>
<td>overall reaction</td>
</tr>
<tr>
<td>2NO₃⁻ + 2.5Cl⁻ + H₂O → N₂(g) + 2.5CO₂(g) + 2OH⁻</td>
</tr>
</tbody>
</table>

5. Effective parameters on performance of BERs

The denitrification efficiency by BERs depend on many parameters, which key parameters in assembling of reactors are: materials, shape, number of electrodes and their arrangement as well as design of BERs [19, 42, 43]. Furthermore, operational and environmental parameters such as pH, HRT, carbon source and EC known as other effective parameters in denitrification by EBRs [44-46]. To reduce some drawbacks in BERs, identify of effects and optimization of these parameters are necessary. According to table 2 previous studies showed that various types of metals and carbons were used as electrode materials; carbon in the form of granular activated carbon (GAC) and graphite as well as metals such as stainless steel, titanium, nickel and copper [40, 46, 47]. Also, various denitrifiers in different condition such as suspended in fluidized bed or immobilized on different permeable media (e.g. soil, GAC, plastic particles, mesh or reticulated planes), have been applied for different treating aqueous solution such as surface and groundwater, municipal and industrial wastewater, aquatic and river water [19].

There are many types of reactors found applications in bio-electrochemical system that have been investigated by researchers. In recent years, researchers to improve denitrification performance, and decrease of hydraulic retention time which before was from 10 h to several days to achieve the complete denitrification [48], have investigated other alternatives for configuration of BERs. Among them integrated systems, tow parts reactor (electrochemical and biological), and multi-electrode systems or three-dimensional (3D) electrode had good results [32, 48, 49]. As sample Wan et al. [32] and Wang and Qu, [49] to improve effectiveness of BERs or eliminate drawbacks of integrated methods combined sulfur limestone autotrophic denitrification method (SLAD) with BER, and developed a new integrates method (bio-electrochemical combine with sulfur autotrophic denitrification (CBSAD). In new novel system, the limestone to pH adjustment is not necessary. Therefore, with consumption of H⁺, which was produced by sulfur denitrification in the bio-electrochemical reactor can prevent increase of hardness in effluent. In addition, the produced CO₂ on anode complement process as inorganic carbon source and pH buffer, and efficiently removed nitrate more than 95% without nitrite accumulation and the sulfate concentration of effluent was lower than 250 mg/L [32]. Two parts reactor “electrochemical cell and bioreactor” is another alternative for BERs. Flexibility in operation and simplifies maintenance are preferences of this configuration. This arrangement is economical, because of separating parts of H₂ generation and biomass. Therefore, it was possible jointing of a small electrochemical cell with a large bioreactor. Moreover, the treated water with this method even in very high nitrate concentrations is proper. In addition, the pH changes is little [50]. The result of several study showed, that suitable denitrification performance with multi-electrode system comparing to previous BERs because of large effective surface area of electrode, the charge transfer mechanism by dissociative electrolyte, and the formation of highly reducing (or oxidizing) [51].

The pH values is one of the main factors for controlling of denitrification because it can be as limit denitrification activity and cause of nitrite accumulation [16]. Base on equation (3) researchers have mentioned during denitrification process when NO₃⁻ change to NO₂⁻, pH has not change. Nevertheless, in second stage (change...
of nitrite to nitrogen gas) pH will increase, and nitrite accumulation occur because of pH elevate, which is one of the main reason for agglomeration of nitrite in denitrification [39, 52, 53]. However, hydrogen as an electron donor has many advantages which were confirmed, but same as traditional biological processes control of pH is also necessary [37].

Some substrates such as carbon, nitrogen, phosphorous, and mineral components have key role on denitrification rate because substrates are necessary to grow up of various species of denitrifying bacteria in pure or mixed cultures [28, 52]. Among them carbon as food and energy source is a important parameter on denitrification rate by two group of denitrifiers “heterotrophic” and “autotrophic” [49, 54]. Researchers mentioned, depend on COD/N ratio of influent may need external carbon in BERs to denitrification of wastewater [19]. They stated when the COD/N ratio of influent is lower than 3.4 gCOD/gN, need to add extra organic matters [55]. Therefore, researchers to improve of nitrate removal in water and wastewater investigated various carbon sources [19, 56, 57] such as methanol, ethanol, sucrose, acetate, industrial and demotic wastewaters, and other industrial wastes [58], also bicarbonate and carbon dioxide [52, 59].

Other important effective parameters on denitrification rate in bio-electrochemical reactor are electric current intensity (I) and hydraulic retention time (HRT), which were investigated by researchers [32, 39, 49, 51]. Results showed when the electric current increased the reduction of nitrate improved. Results show that low and high electric current because of inadequate hydrogen production and excessive hydroxyl generation respectively has low reduction. Also, the efficiency of system was reduced in the low and high HRT because in low (6h) and high (48h) HRT didn’t achieve the required reaction time for microorganisms, and increase rate of flushing unfavorable hydroxyl anions out of the cathode sector [39].

6. Implementation of BERs

The bio-electrochemical reactor process may have a potential for the removal or detoxification of other substances in water and wastewater. Therefore, some investigations have been carried out on remove of various contaminates by using BERs such as simultaneous removal of nitrate and pesticide [60], copper ion [23] or ammonium nitrogen [61, 62].

Some researchers applied sulfur limestone autotrophic denitrification (SLAD) systems for nitrate removal. In this system, limestone is used to adjust the pH, and sulfur use as electron donor. During the reactions 7.54 mg/L sulfate to 1mg-N/L removed nitrate will be produced, which can raise the hardness due to produced Ca²⁺ by the limestone. Therefore, to improve of SLAD researchers developed a new method, which is combining of bio-electrochemical and sulfur autotrophic denitrification (CBSAD). In the new novel system, the limestone to pH adjustment is not necessary. Therefore, for preventing hardness in effluent, the produced H⁺ by sulfur denitrification consume in the bio-electrochemical reactor. In addition, the produced CO₂ on anode complement this system as inorganic carbon source and pH buffer [32, 49].

Sakakihara and Nakayama [51] used a novel multi-electrode system for bio-electrochemical denitrification of water contain 15-20 mg NO₃⁻-N/L. In this reactor, 8 pieces of titanium were located in reactor as cathode, and the anodes were two pieces from Pt-coated. To prevent of leakage O₂ into cathode part was used water-permeable plastic foam between anode and cathode. Results showed suitable denitrification performance with multi-electrode system compare to previous BERs because of large effective surface area of electrode, the charge transfer mechanism by dissociative electrolyte, and formation of highly reducing (or oxidizing). In another research, Prosnansky et al. [26] investigated a multi-cathode biofilm-electrode reactor combined with microfiltration (MF) for treatment of nitrate-contaminated water. The reactor is composed of two compartments (multi-cathode BER and membrane compartments). The BER was divided two part with a Porous sponge-foam rubber to impede inter O₂ bubbles to cathode zone and mixing with H₂. In the BER section cathodes was arranged by 5 porous GAC electrodes, and the anode was designed by platinum-coated titanium that surface area of cathode and anode were 750 and 150 cm², respectively. Results confirmed this novel could perform denitrification with high rates at hydraulic retention time low (20 minute). Furthermore, the efficiency of denitrification rate improved 3–60 times in comparison with previous studies. Also, the cathodic current density decreased because of enlarged surface area of cathodes by multi-GAC electrode system.

Watanaba, T et al. [17] applied a bio-electrochemical reactor (working volume = 5 L, axial center anode carbon rod 16mm diameter, surrounded cathode with 12 carbon rods and 8mm diameter) to treat acidic wastewater containing copper ions and a high concentration of nitrate. The distance between the anode and cathode was about 50mm. Achievements showed an effective removal of copper ions and nitrate, when an electric current was applied and acetate was added as an external electron donor.

Ghafari et al. [39] studied an up flow bio-electrochemical reactor to denitrification of polluted water with biocarrier (GAC) and stainless steel plate as cathode zone. The achieved results for two operating parameters (HRT= 6–36 h) and electric current (I= 0 to 20 mA) were examined on contaminated water containing 20mg NO₃⁻-N/L. The nitrate completely reduced in
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Table 2. Performance of denitrification in BERs

<table>
<thead>
<tr>
<th>Type of reactor</th>
<th>Feed solution (groundwater)</th>
<th>Cathode</th>
<th>Anode</th>
<th>Carbon source</th>
<th>I mA</th>
<th>NO$_3^-$-N mgL$^{-1}$</th>
<th>HRT (h)</th>
<th>% Nitrogen removal</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBSAD$^b$</td>
<td>Groundwater</td>
<td>Stainless steel</td>
<td>Carbon rod</td>
<td>CO$_2$</td>
<td>30-1200</td>
<td>20.9-22.0</td>
<td>4.2-2.1</td>
<td>95 - 100</td>
<td>[32]</td>
</tr>
<tr>
<td>UBER$^c$</td>
<td>Contaminated water</td>
<td>Stainless steel</td>
<td>Stainless steel mesh</td>
<td>NaHCO$_3$</td>
<td>0-20</td>
<td>20</td>
<td>6-36</td>
<td>100</td>
<td>[39]</td>
</tr>
<tr>
<td>3DBER$^d$</td>
<td>Groundwater</td>
<td>Activated carbon fiber</td>
<td>Beta-lead dioxide</td>
<td>CO$_2$</td>
<td>8-32</td>
<td>30</td>
<td>8</td>
<td>99.80</td>
<td>[63]</td>
</tr>
<tr>
<td>BER$^e$</td>
<td>Synthetic wastewater</td>
<td>Graphite felt</td>
<td>Dimensionally stable anode (DSA)</td>
<td>NaHCO$_3$</td>
<td>N/A</td>
<td>20 to 492</td>
<td>1.7 (4)</td>
<td>98</td>
<td>[64]</td>
</tr>
<tr>
<td>BER</td>
<td>Municipal sewage</td>
<td>Stainless steel</td>
<td>Graphite</td>
<td>N/A</td>
<td>20-120</td>
<td>TN=37.2-68</td>
<td>6</td>
<td>75</td>
<td>[40]</td>
</tr>
<tr>
<td>CBSAD</td>
<td>Drinking water</td>
<td>Cylindrical stainless steel</td>
<td>Carbon rod</td>
<td>CO$_2$</td>
<td>2-20</td>
<td>30</td>
<td>1.9-5</td>
<td>90 - 100</td>
<td>[49]</td>
</tr>
<tr>
<td>BER-MF</td>
<td>Synthetic groundwater</td>
<td>GAC with platinum</td>
<td>Pt-coated titanium coated</td>
<td>CO$_2$</td>
<td>40-300</td>
<td>15-40 (25)</td>
<td>0.33-6 (2.88)</td>
<td>80</td>
<td>[26]</td>
</tr>
<tr>
<td>BER +Absorber</td>
<td></td>
<td>Stainless</td>
<td>Amorphous carbon</td>
<td>CO$_2$</td>
<td>0-10</td>
<td>24</td>
<td>10</td>
<td>&gt;95</td>
<td>[37]</td>
</tr>
<tr>
<td>BER</td>
<td>Groundwater</td>
<td>Metal</td>
<td>Pt-coated</td>
<td>NaHCO$_3$</td>
<td>80-960</td>
<td>13.8–20.8</td>
<td>2-6</td>
<td>80</td>
<td>[51]</td>
</tr>
<tr>
<td>BER</td>
<td>Feed solution (groundwater)</td>
<td>Carbon material</td>
<td>Carbon material</td>
<td>NaHCO$_3$</td>
<td>0-100</td>
<td>20</td>
<td>10-13</td>
<td>98</td>
<td>[14]</td>
</tr>
<tr>
<td>BER</td>
<td>Contaminated groundwater</td>
<td>Stainless</td>
<td>Amorphous carbon</td>
<td>CO$_2$</td>
<td>2-10</td>
<td>20</td>
<td>10</td>
<td>100</td>
<td>[65]</td>
</tr>
<tr>
<td>BER</td>
<td>Contaminated groundwater</td>
<td>Stainless</td>
<td>Amorphous carbon</td>
<td>CO$_2$</td>
<td>1–10</td>
<td>20-24</td>
<td>10-50</td>
<td>N/A</td>
<td>[66]</td>
</tr>
</tbody>
</table>

a Units used for HRT (h).
b Combined bio-electrochemical and sulfur autotrophic denitrification system (CBSAD)
C Uplow bio-electrochemical reactor (UBER)
d Three-dimensional bio-electrochemical reactor(3DBER)
e Bio-electrochemical reactor (BER)
electric current range (10–16mA) as well as HRT 13.5–30 h. The removal of nitrate in L=0 was minimum but the nitrate removal was improved by increase of electric current (up to 14mA).

7. Conclusions

On base of review in this work, one of the worldwide contaminations of soil and water has been nitrate contamination as an environmental challenge since many years ago. The pollution of water is a major universal environment anxiety because the continuous consumption of water containing high nitrate levels can be cause many diseases such as methemoglobinemia. Therefore, to achieve acceptable concentration of nitrate base on defended standards, in recent years, the nitrate removal has been considered more than before. Up to now, researchers have applied different kind of methods for nitrate removal from water and wastewater, which the results show denitrification of contaminated water and wastewater by conventional abiotic methods had not suitable efficiency because of many reasons above mentioned. Furthermore, the biological denitrification was defended as admiration method for denitrification but it is not functional method for high concentration of nitrogen components. Therefore, researchers have focused on progress of biological denitrification by creating better correlation between the nitrate and microorganisms. The bio-electrochemical system is new method, which provided the researchers’ objective. The efficiency of bio-electrochemical system was affected by many parameters such as electrodes specifications, pH, carbon source, HRT, and current intensity that are concerned in this review. Notwithstanding all of the mentioned before investigation, there remain many unclear aspects, which can be cause of development and improvement of efficiency of BERs because using this kind of denitrification system become familiar during two decade ago and there is not enough information about performance of system and the effects of operational variations and configuration of reactor. Therefore, to develop of this method need to more and more researches, especially with concentrate on investigating of configuration of reactor such as arrangement, shape, and material of electrodes. Furthermore, in the case of sewage treatment applying BERs, the applicable hydraulic retention times, pH, carbon source, and current intensity are still a subject of argument.

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References

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