Effect of low temperature on the performance of UASB reactor for municipal wastewater treatment: recent advances and future perspectives

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Abstract. Upflow anaerobic sludge blanket (UASB) reactor is a widely used anaerobic treatment technology, which is essential in municipal sewage treatment, in tropical and subtropical areas. However, UASB reactors have been underutilized in low-temperature zones due to the poor performance of UASB reactors under psychrophilic conditions. This study has three primary purposes: to review the performance of UASB reactors with different parameters, to describe the limiting factors at low temperatures, and to prospect the future solutions. In the low-temperature environment, lower COD removal efficiency and production of methane in the UASB reactor have been observed in various studies. The key limiting factors are increased dissolved methane, decreased activity of methanogens and hydrolytic bacteria. This article proposed that five technologies could reduce the impact of low temperature on the treatment of municipal wastewater by the UASB reactor, which are denitrifying anaerobic methane oxidation (DAMO), direct interspecies electron transfer (DIET), bio-electrochemical systems (BES), pre-hydrolysis, and degassing membrane (DM). These technologies are promising to be developed into highly-efficient engineering strategies for treating municipal wastewater in the UASB reactor at low temperatures in the future.

1 Introduction

Anaerobic technology is a widely used wastewater treatment technology that has attracted considerable research attention [1]. Compared with aerobic treatment technology, anaerobic treatment technology exhibits several clear advantages, namely, lower energy consumption, lower sludge production, energy recovery as methane, and the ability to withstand higher organic loads [2]. Upflow anaerobic sludge blanket (UASB) reactor, a typical anaerobic technology, is only applicable to municipal sewage treatment in tropical and subtropical areas, such as Brazil and Malaysia [3, 4]. However, the UASB reactor is rarely used in low-temperate regions, mainly due to poor performance caused by the low activity of methanogens and hydrolytic bacteria.

Many researchers have conducted intensive researches on the influence of low temperatures on UASB reactors and provided insights into mechanism elucidation. This paper mainly explored the performance of the UASB reactors treating municipal sewage at low temperatures, summarized the limitations and constraints in practical applications, and proposed possible solutions. At the end of the article, the challenges and future prospects of treatment efficiency, and recovery of COD and nitrogen in the UASB reactors at low temperatures are discussed.
2 State of the art of anaerobic sewage treatment

Anaerobic technology started in France more than 100 years ago in 1860 but was not widely implemented until the invention of UASBs in 1970 [5, 6]. Temperature is one of the key factors affecting the performance of the UASB reactors. Researchers conducted relevant experiments at 10 °C–20 °C to promote the application of UASB reactors in the field of low-temperature digestion.

Table 1 summarized the literature data on the scale and performance of UASBs treating municipal wastewater treatment at low temperatures. The upflow velocity, as a factor that affects the performance of the UASB reactors, varied in the range of 0.02~0.53 m/h. If the upflow velocity is excessively high, then the sludge was washed out with an increased sludge loss rate. However, excessively low upflow velocity would reduce the contact between microorganisms and the sewage; thus, the reactor will not be thoroughly mixed [7]. The HRT in the table is within the range of 4~24 h. If the HRT is excessively high, then the organic loading rate is reduced, resulting in a lower treatment capacity. By contrast, if the HRT is too low, then the treatment process of the UASB reactor cannot be carried out completely [8].

The influent COD concentration of different reactors was 114-1200 mg/L, with the COD removal efficiencies ranged from 31.8 to 83%. Under the condition of 15 °C with an OLR of 6.94 g COD/L/day, the COD removal efficiency of 31.8% cannot meet the requirements of the effluent discharging standard. In Table 1, the COD removal efficiency of different UASB reactors is above 65% at 20 °C. The methane production was in the range of 0.046-0.47 g CH4-COD/g influent COD.

3 Current limitations and constraints at low temperatures

The decrease in temperature will change the physical and chemical properties of municipal wastewater and subsequently affect the performance of the reactor. The main impacts are dissolved methane (D-CH₄) and the activity of methanogenic bacteria and hydrolytic bacteria [9].

3.1 Dissolved methane

The solubility of methane increases with decreasing temperature, thereby indicating that D-CH₄ is a limiting factor. Bandara et al. measured the concentration of D-CH₄ in the UASB reactor at different temperatures of 35 °C and 15 °C and obtained an average concentration of 63 and 104 mg COD/L, respectively. [10]. When the effluent from the UASB reactor is pumped into the subsequent reactor, the internal pressure of the subsequent reactor will increase. D-CH₄ will transform into gaseous methane and enter the atmosphere again [11]. The following methods can solve the problems of D-CH₄: using the degassing membrane (DM) to recover methane or converting D-CH₄ into carbon dioxide. Among

| OLR (g COD/L/day) | Location | Volume per reactor (L) | HRT (h) | Upflow velocity (m/h) | Temperature (°C) | Influent COD mg/L | Influent TSS mg/L | Effluent COD mg/L | Effluent TSS mg/L | Removal efficiency % | References |
|------------------|----------|------------------------|---------|-----------------------|------------------|------------------|------------------|------------------|------------------|---------------------|------------|
| 11               | Japan    | 21.5                   | 4.7     | 0.43                  | 13               | 114              | -                | 62.7             | -                | 45                  | 0.35       | [4]        |
| 0.8-1.2          | Canada   | 8                      | 10      | 0.10                  | 20               | 272              | -                | 48               | -                | 82                  | -          | [12]       |
| 0.73             | Netherlands | 500                  | 6       | 0.43                  | 16.5             | 224.2            | -                | 68.5             | -                | 69                  | -          | [13]       |
| 5.0              | Israel   | 5.3                    | 24      | 0.35                  | 14               | 340              | 428              | 102              | 60               | 86                  | 0.046      | [14]       |

Table 1. Parameters and indicators of different reactors
the above methods, DM shows sustainable promises in application due to its ability to recover CH$_4$. Furthermore, the conversion of D-CH$_4$ to CO$_2$ is an energy-consuming process that cannot recover CH$_4$. Thus, the DM is an important research topic that can effectively separate dissolved gases from liquids mainly because only gas molecules can pass through the nonporous layer in DM [21]. Bandara et al. measured the average concentration of D-CH$_4$ emitted from UASB and UASB + DM reactors at 51 ± 12 mg COD/L and 22 ± 4 mg COD/L, respectively [21]. Despite its efficient CH$_4$ recovery, the DM is rarely used due to its high cost, short service life, and membrane pollution problems [22].

3.2 Activities of methanogenic bacteria

The specific methanogenic activity (SMA) of methanogens will significantly decrease with decreasing temperatures. The SMA at 35 °C is more than twice of that at 10 °C in Zhang’s study [23]. Similarly, Xu et al., found that the SMA at 12 °C was 2-8 times lower than the SMA at 37 °C [20]. For the problem of low activity of low-temperature methanogens, the researchers came up with some improvement measures: Petropoulos et al. isolated methanogenic colonies exposed to the low-temperature environment in the alpine area, and inoculated these methanogenic colonies (cold-adapted colonies) in the UASB reactor. The specific activities of methanogens were 6.3, 7.6 and 10.3 fmol CH$_4$ cell$^{-1}$ day$^{-1}$ at 4 °C, 8 °C, and 15 °C, respectively. The specific activity of methanogens was 10 times higher than that without cold-adapted bacteria at the same temperature. Bio-electrochemical systems (BES) is another option. In the BES system, the electron donor is oxidized at the anode to release electrons. When power is supplied to the system, the released electrons are transferred to the cathode to produce H$_2$, then CH$_4$ is produced from the combination of CO$_2$ and H$_2$ [24]. Tian et al. set up three UASB reactors with the following similar specifications: R1 without electrode; R2 with electrodes but no electricity; R3 with energized electrodes, that is, using the BES. When the temperature dropped from 12 °C to below 8 °C in the experiment, the CH$_4$ yield of R1 and R2 dropped to 4.5 ± 0.3 and 5.3 ± 0.2 mL/g VSS/d, and the CH$_4$ yield of R3 did not fluctuate significantly (12.1 ± 0.1 mL/g VSS/d). The results show that BES can relatively maintain methanogenic activity at low temperatures because the enriched hydrogenotrophic methanogens and electroactive bacteria are tolerant of the low-temperature conditions. Overall, the above-mentioned methods can reduce the effect of low temperature on methanogenic activities [25].
3.3 Activities of hydrolytic bacteria

The core process of hydrolysis demonstrates that hydrolytic enzymes released by the hydrolytic bacteria convert macromolecular insoluble organic matter into small molecule soluble organic matter [26]. Since the activity of hydrolytic bacteria will reduce with decreasing temperature, the hydrolysis process is one of the rate-limiting steps of anaerobic treatment process [20]. For instance, Ferreiro, et al., reported that the hydrolysis constant of 0.038 d\(^{-1}\) at 20 °C is 3.4 times higher than 0.169 d\(^{-1}\) at 10 °C [27].

Some researchers used the modified UASB + digester system to solve the problem of the hydrolysis speed limit at low temperatures. The sludge activity in the UASB reactor was reduced due to the low-temperature environment of 10 °C. The hydrolysis rate of sludge accelerated and the CH\(_4\) production increased when the sludge from the UASB reactor entered the digester at 35 °C and was then recycled to the UASB reactor [20]. The researchers proposed another solution called pre-hydrolysis. Zhang, et al., conducted a short-term pre-hydrolysis test with and without pre-hydrolysis of cellulose and tributyrin at 35 °C. The results showed that the low-temperature anaerobic hydrolysis rate constant increased by 1.5-10 times when short-time anaerobic prehydrolysis is adopted at 35 °C. These methods can solve the influence of low temperature on hydrolysis activities as following: before entering the UASB reactor, the solids and liquids are separated. The solids are added to a higher temperature reactor for hydrolysis. The effluent is then injected into the UASB reactor [28].

4 Prospect

This article summarizes the inhibitory effect of low-temperature conditions on the efficiency of UASB reactors treating municipal sewage, and also provides various solutions according to different constraints. Meanwhile, some novel strategies for mitigating the impacts of low temperature on AD processes are still being explored.

The denitrifying anaerobic methane oxidation (DAMO) step is a possible solution to reuse D-CH\(_4\) in the effluent. In the DAMO process, microorganisms use methane to provide electrons. Nitrate and nitrite are electron acceptors that convert methane and nitrate nitrogen into CO\(_2\) and N\(_2\). Therefore, the DAMO process not only consumes the D-CH\(_4\), but also converts NH\(_4^+\) to N\(_2\). DAMO is an energy-saving process and additional carbon is unnecessary compared with the denitrification process [29]. Wang, et al., reported that the maximum nitrogen removal rate of the ordinary UASB reactor was 37.8 mg N L\(^{-1}\) d\(^{-1}\). They designed a membrane bioreactor to enrich DAMO microorganisms, and found that the removal rates of nitrate and ammonium nitrogen increased to 190 mg N L\(^{-1}\)d\(^{-1}\) and 60 mg N L\(^{-1}\)d\(^{-1}\), respectively. Therefore, DAMO has broad application prospects in the anaerobic treatment of municipal sewage. However, there are still many challenges in the DAMO process. For example: the current DAMO process is still limited to laboratory scale [30]. The functional microorganisms during the DAMO process grow very slowly [31]. Furthermore, biogas in DAMO containing CO\(_2\), H\(_2\), and H\(_2\)S provides unnecessary inhibition on the growth of microorganisms [32, 29].

Direct interspecies electron transfer (DIET) is another possible solution. DIET refers to the direct transfer of electrons between electron donor and electron acceptor microorganisms [33]. There are two mechanisms for the DIET process: one mechanism is the process of electron exchange between microorganisms through their own conductive structures such as conductive pili and cytochrome-c [34]. The other is that microorganisms use exogenous non-biological conductive materials such as granular activated carbon, biochar, or carbon nanotubes to achieve the DIET process [35]. The advantage of the DIET process is that it does not require H\(_2\) and acetic acid produced by the anaerobic digestion as intermediates, which improves the efficiency of anaerobic digestion [36]. Lin et al. evaluated the enhanced effect of graphene, a conductive carbon material, on the anaerobic digestion of ethanol. The results showed that the yield of biomethane increases by 25.0% after adding graphene of 1.0 g/L [36]. Many challenges still exist in the current DIET process. For example: the addition of non-biological conductive materials will increase the cost of DIET [37]. At the current stage, researchers have a very limited understanding of the DIET process in an anaerobic environment [38].
5. Conclusion
As a typical reactor in anaerobic treatment technology, the UASB reactor faces numerous challenges when operating under psychrophilic conditions, such as low efficiencies in hydrolysis, COD removal, and methane production. These challenges will lead to the poor performance of the UASB reactor at low temperatures. The increased D-CH$_4$ and the inferior activity of hydrolytic bacteria and methanogens are the main limiting factors of the reactor. DAMO, DIET, BES, prehydrolysis, and DM technologies are proposed as promising solutions to deal with different limiting factors and reduce the impacts of low temperature on the performance of UASB reactors. This review provides solid and thorough insights into the application of anaerobic treatment technology in low-temperature environments.

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