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Review Article

Biodegradation of Toxic Compounds by Aerobic Granulation Technology

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Abstract

Aerobic granulation technology is a strong contender to replace conventional wastewater treatment processes. Aerobic granules are microspheres of self-immobilized microorganisms and they can be easily separated from the liquid phase as they settle many times faster than sludge flocs. Biodegradation of toxic compounds is a crucial area where traditional wastewater treatment processes are still struggling. It is a relatively new research area for aerobic granulation technology, but it holds the key for this technology to establish itself as an effective alternative of present day wastewater treatment processes. This review covers the mostly explored toxic compounds which have been successfully treated by aerobic granulation technology. Present research trends of this technology in biodegradation of toxic compound have been critically analyzed to identify the future research directions. In addition to a summary of different reports, authors' own opinions on this subject have been presented.

Introduction

Aerobic granulation technology is a new generation of biological wastewater treatment technology. The drawbacks of traditional activated sludge process of wastewater treatment were reduced by introducing more advanced enhanced biological nutrient removal processes. Aerobic granulation technology has the potential to replace the modern day enhanced biological nutrient removal processes. Aerobic granules are round shape self-immobilized microbial aggregates with a diameter of around 1 to 3 mm. These are bigger and stronger than sludge flocs found in traditional wastewater treatment process which are usually 30 to 200 µm in size [1]. They settle faster than sludge flocs and it helps to rapidly separate the liquid and solid fractions of the wastewater [2,3]. They are able to settle as high as around 10 times faster than sludge flocs [4]. Dense structure and fast settling ability of the aerobic granules help in reducing sludge volume and enhance dewater ability. Moreover, aerobic granules are able to deal with high strength wastewater and high organic loading rate [5]. They also exhibit high toxicity tolerance [6,7]. Formation of aerobic granules allows the process to retain high biomass concentration [6-8]. In general, the aerobic granulation technology allows using three to five times more biomass to treat the same volume of wastewater [9]. It is a crucial advantage as it allows rapid treatment of a large amount of wastewater within a small space. To treat the same volume of wastewater, an aerobic granular sludge process would require only one fifth of the space occupied by a conventional activated sludge based wastewater treatment plant [9]. Thus, around 80% reduction in land use will be possible if aerobic granulation technology is used to replace conventional wastewater treatment plants [10]. Therefore, aerobic granulation technology has a very small foot print [11].

Aerobic granules are produced in Sequencing Batch Reactors (SBR) [8]. SBRs create cyclic feast and famine conditions and it is considered to be a factor behind aerobic granule formation [8]. Formation of anaerobic granules was known before the aerobic granulation technology was developed. Aerobic granules can overcome the disadvantages of anaerobic granules such as high process temperature and long time required for process development [6,7]. It has been reported that aerobic granulation technology can deal with an organic loading rate as high as 15kg COD/m^3/day [12]. However, unlike anaerobic granules, it can be operated under a relatively low organic loading rate. Thus, aerobic granulation technology is a promising new technology of wastewater treatment.

One of the major drawbacks of most modern wastewater treatment processes is that they are unable to completely remove various toxic contaminants from the wastewater. These compounds could be human or veterinary antibiotics, synthetic textile dyes, endocrine disrupting compounds such as bisphenol A and some herbicides and pesticides. If the aerobic granulation technology would be able to effectively remove such pollutants from the wastewater, it would become a strong contender to replace conventional wastewater treatment processes. In this context, biodegradation of some important pollutants by aerobic granulation technology has been reviewed in this article.

Biodegradation of Dyes

Textile industry is the single largest consumer of synthetic dyes [13]. Cosmetic, pharmaceutical and paper industries are some other major industries to use dyes. Dyes may not be as toxic as any

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other pollutants to the ecosystems, but they may destroy the natural beauty of the water bodies and the water may become less attractive for further use (e.g., drinking water) [13]. Aerobic granulation technology has been used to treat different industrial wastewaters containing synthetic dyes. Reactive blue 59, acid red 18, Congo red and eriochrome black T are some of the dyes that have been successfully treated by aerobic granulation technology.

Kolekar et al. have used textile wastewater sludge to develop aerobic granules and reactive blue 59 removal by these granules were investigated. The authors have determined that the granules were capable of efficiently removing the dye and the metabolites produced during the biodegradation studies were not toxic [14]. Sadri et al. have used sequencing batch reactor operated at alternating anaerobic-aerobic mode to develop aerobic granules for biodegradation of acid red 18. According to the authors, the granules were stable at acid red 18 concentrations as high as 50mg/L. However, at higher concentration (100mg/L), loosely attached extracellular polymeric substances were extensively produced and both stability and dye removal efficiency of the granules were reduced [15]. Ma et al. have used sequencing batch reactor to develop aerobic granules using activated sludge. The authors have reported that the granules were capable of removing around 90% of Congo red added to the reactor [16]. Hailei et al. have used Phanerochaete sp. HSD to produce very small fungal granules. These small granules were used as seeds to initiate aerobic granule formation. The mature granules obtained by this method were used to degrade the azo dye eriochrome black T. The authors have reported that the granules were capable of dealing with high eriochrome black T load and the dye decolorization efficiency was superior to that of aerobic granules prepared by conventional method [17].

Muda et al. have concluded that combined aerobic-anaerobic biodegradation could be effective for dye removal from wastewater. According to the authors a hybrid biogranular system could be useful in treating the wastewater containing synthetic dyes [18]. Muda et al. have used anaerobic granules as seed to develop granular sludge by using alternative aerobic-anaerobic conditions. Synthetic textile wastewater containing a mixture of different dyes was used to develop these granules. According to the authors, the granules were capable of removing 56% and 93% of color and COD, respectively [19]. Ibrahim et al. have developed loose aerobic microbial flocs by using textile wastewater. The flocs were able to settle down very quickly and color and COD removal efficiencies were 70% and 55%, respectively [20]. Muda et al. have developed granular sludge to remove dyes from synthetic textile wastewater. Textile mill wastewater sludge, mixed sewage sludge and seed granules from Anaerobic Sludge Blanket Reactor (ASBR) were used to develop these granules. The authors have reported that under alternating aerobic-anaerobic condition, the granules with an average diameter of 2.3±1.0 mm could be developed. Color, ammonium and COD removal efficiencies of the granules were around 62%, 95% and 94%, respectively [21].

Certain fungi, either in pure or in mixed culture condition, can develop spherical pellets similar to that of aerobic granules. Hai et al. have used pellets of *Coriolus versicolour* to remove acid orange 7, an azo dye, from synthetic wastewater. The authors have reported that the pellets were capable of removing around 99% of the dye. However, gradually pellets were contaminated by bacteria leading to their disintegration and decrease in the dye removal efficiency [22]. Aerobic granules made up of mixed microbial culture are less susceptible of any contamination by bacteria. Therefore, they could be considered to replace fungal pellets in dye removal. In a similar study, Sathian et al. have used sequential batch reactor for dye removal from textile wastewater by four different strains of fungi [23]. Considering potential contamination of fungal pellets by bacteria during real wastewater treatment, aerobic granules might be better choice in terms of physical stability and removal efficiency.

Biodegradation of Antibiotics

Presence of antibiotics in the final effluent of wastewater treatment process is a global concern. Even modern wastewater treatment plants of developed nations are not able to assure complete removal of antibiotics. According to Watkinson et al. cephalexin (4.6ppb) and ciprofloxacine (3.8ppb) are the two antibiotics detected in relatively high concentration in wastewater [24]. Cefaclor (0.5ppb), sulphamethoxazole (0.36ppb) and trimethoprim (0.34ppb) were other antibiotics frequently found in wastewater [24]. Addition of antibiotics in the wastewater was found to increase the number of bacteria with antibiotic resistance gene [25]. Municipal wastewater may be contaminated with antibiotics mostly by human excreta. Slaughter house wastewater or the wastewater from animal farms may also contain a considerable amount of antibiotics. Swine wastewater is well-recognized to contain a large amount of antibiotics [26]. Likewise, the wastewater of pharmaceutical and personal care product industry may contain various antibiotics. Therefore, in order to protect the ecosystem from antibiotic resistance development, removal of antibiotics from all short of wastewater is necessary.

Aerobic granulation technology has been evaluated to remove antibiotics from wastewater. Zhao et al. have used aerobic granular sludge membrane bioreactor to remove antibiotics from pharmaceutical and personal care products wastewater. The authors have reported that the reactor was capable of removing different drugs such as naproxen and prednisolone. However, it was not useful for removal of antibiotic (amoxicillin) [27]. Liu et al. have demonstrated that presence of antibiotics in influent wastewater can significantly reduce the COD and ammonia removal efficiency of aerobic granules. Moreover, the authors have reported that presence of antibiotics in the influent wastewater was capable of increasing the number of antibiotics resistant bacteria within the aerobic granules [28]. Li et al. have concluded that the activated sludge can remove tetracycline mostly by adsorption and contribution of biodegradation is negligible [29]. Therefore, in addition of biodegradation, antibiotics adsorption by aerobic granules should be investigated. Cetecioglu et al. have investigated the biodegradation of tetracycline under methanogenic, sulfate-reducing and nitrate-reducing conditions. The authors have reported that around 46% of the antibiotics could be degraded under methanogenic conditions. However, sulfate and nitrate-reducing conditions were not favorable for biodegradation of the pollutant [30]. Therefore, aerobic granules maintained under methanogenic conditions might be useful for tetracycline biodegradation. Huang et al. have investigated sulfamethazine removal in aerobic sequence batch reactor. The author have reported that by increasing the sludge retention time to around 25days, around 80% of the antibacterial agent could be removed [31]. Therefore, a similar study involving aerobic granules would shed light on the potential of this technology.

Zou et al. have evaluated antibiotic resistance gene transmission potential of granular and flocculent sludge. The authors have concluded that the application of granular sludge for wastewater treatment can reduce the transmission of antibiotic resistance gene [32]. Li et al. have reported that at pH3, anaerobic granular sludge can remove as high as 93% of the antibiotic tetracycline. The authors have demonstrated that by increasing the temperature from 25 to 40ºC, tetracycline removal efficiency could be increased from 2.98 to 4.61 mg/g [33]. In a similar study, Shi et al. have investigated tetracycline removal by nitrifying granular sludge. According to the authors, the nitrifying granules were capable of quick sorption followed by slow biodegradation of tetracycline [34]. Fluoroquinolones antibiotics such as, ciprofloxacin and ofloxacin can reduce the phosphorus removal efficiency of aerobic granular sludge. Shock loading of these antibiotics can initiate disintegration of the granule, which in turn can reduce the sludge bed volume. However, ammonium oxidizing and nitrite oxidizing activities of the granules were not affected by the presence of these antibiotics [35]. Overall, it can be concluded that aerobic granulation technology can be used to remove a range of antibiotics from the wastewater. Sorption and biodegradation are the major mechanisms of antibiotics removal by aerobic granules. Shock loading of antibiotics may disintegrate the granules. Only a few reports are available on antibiotics removal by aerobic granulation technology. The reports indicate that only a partial removal of the antibiotics has been achieved so far. Antibiotics removal potential of the aerobic granules needs further investigation using real wastewater containing antibiotics. Study conducted using wastewater artificially contaminated with a relatively higher concentration of antibiotics may not be useful to evaluate the actual potential of this technology.

Biodegradation of Bisphenol-A

Bisphenol-A is an endocrine disrupting compound, which cannot be completely removed by conventional wastewater treatment process. Li et al. have studied the performance of aerobic granular sludge in presence of Bisphenol-A. The authors have concluded that Bisphenol-A has inhibitory effect on heterotrophic and nitrifying microorganisms of aerobic granules. Moreover, the addition of Bisphenol-A can change the composition of the extracellular polymeric substances of the aerobic granules [36]. Balest et al. have successfully used aerobic granular biomass in a sequencing beach biofilter reactor for Bisphenol-A degradation. The authors have reported that within the experimental period of 4 months, around 93% degradation of the compound could be achieved [37]. Margot et al. have evaluated the aerobic granular sludge technology for removal of 36 different micro-pollutants. The authors have reported that under simultaneous nitrification condition, more than 80% of Bisphenol-A could be removed by the aerobic granular sludge technology [38]. In another study, the effect of Bisphenol-A concentration on nitrogen removal efficiency of aerobic granular sludge was investigated. The authors have reported that around 4mg/L of Bisphenol-A has no effect on nitrogen removal efficiency of aerobic granular sludge. However, Bisphenol-A concentration of more than 4mg/L can reduce the nitrogen removal efficiency by a few percent [39]. Chen et al. have reported that biodegradation of Bisphenol-A could be correlated to acute toxicity of activated sludge flocs. The authors have used relatively high (7.5 to 40 mg/L) concentration of Bisphenol-A for their study [40]. It would be interesting to study Bisphenol-A biodegradation at relatively low or at actual concentration found in the wastewater and its effect on the granules.

Banihashemi et al. have investigated the effect of Sludge Retention Time (SRT) on biosorption of Bisphenol-A by activated sludge. The authors have concluded that SRT can influence the sorption kinetics of Bisphenol-A and highest sorption rate was found at a SRT of 10 days [41]. Yang et al. have investigated biodegradation and biosorption of Bisphenol-A in a membrane bioreactor developed using the fungus *Trametes versicolor* (ATCC 7731). The authors have concluded that biodegradation was the major mechanism of Bisphenol-A removal and as high as 80 to 90% of the pollutant could be removed by this approach [42]. From the above discussion it can be concluded that simultaneous biodegradation and biosorption of Bisphenol-A is a good option for its removal from municipal and industrial wastewater. However, aerobic granulation technology is a relatively unexplored option for Bisphenol-A removal. Aerobic granulation technology allows maintaining high biomass concentration for wastewater treatment. It increases the chance of Bisphenol-A removal, both by biodegradation and biosorption.

Biodegradation of Fluorinated Compounds

Aerobic granulation technology can be used for biodegradation of fluorinated compound such as 2-fluorophenol. In an investigation on biodegradation of 2-fluorophenol it has been observed that aerobic granules without any known 2-fluorophenol degrading bacteria were not capable to remove the pollutant. However, bioaugmentation of the granules with a strain known to degrade 2-fluorophenol had resulted in complete degradation of the target compound [43]. Duque et al. have used *Rhodococcus* strain FP1 to bio-augment aerobic granule for 2-fluorophenol biodegradation. Further the authors have isolated another strain of *Rhodococcus* and a strain of *Pimelobacter* from the 2-fluorophenol degrading granule developed during the study [44].

As already discussed, in addition to biodegradation, aerobic granules can remove pollutants by biosorption. It has been demonstrated that three fluoroquinolone antibiotics; namely, ciprofloxacin, ofloxacin and norfloxacin can be partially removed by biosorption using aerobic granules. The study also suggests that pH of the medium can greatly influence the biosorption of these compounds by aerobic granules [45]. Moreira et al. have investigated the biodegradation of fluoxetine in granular sludge sequencing batch reactor and the effect of this compound on nitrogen and phosphorus removal efficiency of the reactor. The authors have reported that no biodegradation of the compound was observed and ammonia and phosphorus removal was initially affected [46]. Wang et al. have investigated fluoride removal by aerobic granules. Ce (III) was incorporated to the aerobic granules to developed Ce (III) modified aerobic granules. The authors have reported that the modification increased the fluoride removal efficiency of the granules by 359% and each gram of the granules was capable of removing as high as 45.80mg of the pollutant [47]. Zhao et al. have investigated aerobic biodegradation of 4-Fluoroaniline, 2,4-Difluoroanilines, and 2,3,4-Trifluoroanilines. The authors have reported that 100 to 200 mg/L of these compounds could be completely degraded by mixed microbial culture [48]. This study suggests that aerobic granulation technology would be able to remove these compounds from contaminated wastewater. From the above discussion it has been concluded that biodegradation and biosorption of fluorinated compounds is a relatively unexplored area of aerobic granulation technology and it has the scope for further investigation.

Biodegradation of Herbicides/Pesticides

Ma et al. have investigated biodegradation of 2,4-Dichlorophenoxyacetic acid, a herbicide, by aerobic granulation technology. The authors have studied simultaneous biodegradation of 2,4-Dichlorophenoxyacetic acid and its parent compounds. Aerobic granules ware bioaugmented by *Pseudomonas putida* SM1443 strain which had carried pJP4 plasmid from *Ralstoniaeutropha* JMP134. This plasmid encodes some enzymes responsible for degradation of 2,4-Dichlorophenoxyacetic acid and its parent compounds (chlorophenols). Nearly complete degradation of the herbicide and its parent compounds has been achieved [49]. Quan et al. have investigated horizontal transfer of the plasmid pJP4 to aerobic granular sludge. The plasmid was first transferred to an Alcaligenes sp. The Alcaligenes sp. containing the plasmid was used to bioaugment aerobic granular sludge for biodegradation of 2,4-dichlorophenoxyacetic acid. The authors have reported that the strategy was successful with around 12-1498% increase in 2,4-dichlorophenoxyacetic acid removal efficiency [50].

p-Nitrophenol is raw material for manufacturing the pesticides methyl parathion and ethyl parathion. Environmental protection agency of the United States has listed it as one of the priority pollutants. Yi et al. have evaluated aerobic granulation technology for biodegradation of p-Nitrophenol. The authors have reported that a maximum specific degradation rate of 39.3mg p-Nitrophenol/g volatile suspended solid/h could be achieved by this technology [51]. Zhu et al. have investigated biodegradation of 4-Chloroaniline by aerobic granulation technology. Chloroaniline is an intermediate of different pesticide and herbicide manufacturing processes. The authors have reported that 4-Chloroaniline removal efficiency of around 99.9% could be achieved by the aerobic granulation technology [52]. Zhu et al. have used aerobic granules for biodegradation of chloroaniline by using a sequencing airlift bioreactor. In order to acclimatize the granules for chloroaniline biodegradation, the loading rate of the pollutant was gradually increased over a long period of time. The authors have demonstrated that the acclimation strategy was successful to degrade as high as 99.9% of the pollutant [53]. Zhu et al. have investigated 4-chloroaniline biodegradation by aerobic granular sludge in a sequencing airlift bioreactor. Granules were developed from aerobic sludge and they were acclimatized for 4-chloroaniline biodegradation by gradually exposing to increasing concentrations of the pollutant. According to the authors, the granules were efficient in 4-chloroaniline removal and β-Proteobacteria (61.28%) was the dominant microorganism. Thauera, a genus related to β-Proteobacteria, has been identified as the main organism probably responsible for 4-chloroaniline degradation [54].

Baczynski et al. have demonstrated bioremediation of pesticide contaminated soil by granular sludge. DDT, methoxychlor and γ-hexachlorocyclohexane were the target compounds for this investigation. The authors have reported that around 80 to 90% of these pollutants could be successfully removed by methanogenic granular sludge. Addition of 0.5mM Tween 80 was found to further enhance the removal efficiencies of these pollutants [55]. Organophosphorous compounds, such as dibutylphosphite, are used as pesticides. Reddy et al. have developed aerobic granules for biodegradation of dibutylphosphite. The authors have reported that within 8 hours the granules were able to completely degrade around 3mM of the compound. Sphingobium sp. and Acidovorax sp. were the two bacterial strains isolated from the granules, which were capable of using dibutylphosphite as the only substrate [56]. Pentachlorophenol is an herbicide which is toxic to the microorganisms and conventional biodegradation methods are not effective to degrade this compound. Potential application of the aerobic granulation technology for biodegradation of pentachlorophenol has been evaluated by Lan et al. [57]. Terbutryn and irgarol are pesticides which can be removed from the wastewater by aerobic granulation technology. Margot et al. have evaluated terbutryn and irgarol removal by nitrifying aerobic granules developed in a sequencing batch reactor. The authors have reported that more than 60% of these compounds could be removed by nitrifying aerobic granules along with around 20 other pollutants [38]. Monsalvo et al. have evaluated biodegradation of 2-Methyl-4-Chlorophenoxyacetic Acid (MCPA), an herbicide, in a granular sludge bed reactor. The authors have reported that partial biodegradation of 2-methyl-4-chlorophenoxyacetic acid could be achieved by the technology [58].

Biodegradation of Phenols

Jiang et al. have investigated phenol biodegradation by aerobic granulation technology and the microbial strains responsible for this activity. The authors have reported that phenol degrading aerobic granules were dominated by β-Proteobacteria as well as gram positive bacteria having a high G+C ratio. During this study, 10 phenol degrading microbial strains were isolated from the aerobic granules [59]. Ho et al. have demonstrate that aerobic granules acclimatized for phenol degradation were able to efficiently degrade phenol at a concentration as high as 5000mg/L; whereas, activated sludge could withstand only around 3000mg/L of phenol in the wastewater [60]. Adav et al. have isolated a phenol degrading microbial strain from aerobic granules. The strain identified as *Candida tropicalis* demonstrated high phenol toxicity tolerance and were capable of degrading as high as 390mg of phenol per gram volatile suspended solid per hour [61].

Liu et al. have demonstrated that aerobic granules with a size of around 2.54mm have higher level of phenol toxicity tolerance than sludge flocs [62]. Likewise, Adav et al. have isolated an Acinetobacter sp. from aerobic granules. The strain was capable of effectively degrading phenol at a concentration as high as 1000mg/L. However, at a concentration of 1500mg/L of phenol, the strain was unable to grow in free-cell suspended culture condition [63]. Ho et al. have developed aerobic granules made up of only one strain. Phenol degrading strain *Corynebacterium* species DJ1 was chosen for this purpose. The authors have reported that the granules were efficient in phenol degradation and were able to tolerate as high as 2000mg/L of phenol [64]. Tay et al. have used sequencing batch reactors to develop aerobic granules capable of degrading high concentration of phenol. Phenol concentration in the influent wastewater was gradually increased from 1.5 to 2.5 kg phenol/m^3/d. The system was able to maintain high biomass concentration and complete degradation of phenol has been reported [65].

Khan et al. have investigated phenol biodegradation potential of aerobic granules at a phenol loading rate of around 3.9 kg/ m^3/d. The authors have reported that the granules were capable of complete removal of as high as 650mg/L of phenol within 240 minutes [66]. Lee et al. have reported that aerobic granular sludge was more effective than suspended sludge in removing 4-chlorophenol from the wastewater [67]. From the above discussion it is clear that phenol biodegradation by aerobic granules has been extensively investigated by various researchers. It has been established that granular structure of the biomass is able to confer some degree of phenol toxicity tolerance to the microorganisms. Reported phenol degradation rate is impressive and the technology has the potential to be used for phenol containing industrial wastewater treatment.

Biodegradation of Volatile Organic Compounds

This section covers biodegradation of some important volatile organic pollutants which are not discussed in the previous sections. Tert-Butyl Alcohol (TBA), Methyl Tert-Butyl Ether (MTBE) and Trichloroethylene (TCE) are some of the volatile organic compounds which could be removed by aerobic granulation technology. Tay et al. have used sequencing batch reactor for TBA removal by aerobic granulation technology. The authors have gradually increased the influent concentration of TBA from 100mg/L to 600mg/L within a period of nearly 100 days. This acclimatization strategy was successful to achieve nearly complete removal of TBA and effluent concentration of the pollutant was always below detection limit (25µg/L) [68].

Zhang et al. have evaluated MTBE removal by aerobic granulation technology. A sequencing batch reactor was used for this purpose and ethanol was used as co-substrate. The authors have reported that more than 99% removal of MTBE could be achieved and effluent concentration of the pollutant was in the range of 15 to 50µg/L. MTBE degrading organisms such as *Hyphomicrobiumvulgare, Methylobacterium* sp. and *Sphingomonas* sp. was detected in the reactor [69]. In another study involving aerobic granules, Zhang et al. have demonstrated that by increasing the initial MTBE concentration to around 400mg/L, maximum specific MTBE removal efficiency could be achieved. However, further increase in MTBE concentration was resulted in substrate inhibition [70]. Likewise, MTBE degradation by aerobic granular sludge was investigated by Zhengxin et al. The authors have demonstrated that influent MTBE concentration as high as 650mg/L could be treated by the technology. MTBE was used as the only substrate and around 98% removal of the pollutant could be achieved. Out of this 98%, around 25% was volatilized [71].

Zhang et al. have evaluated TCE degradation by aerobic granulation technology and its effect on phenol degradation. The authors have mentioned that high TCE concentration had no visible effect on phenol degrading aerobic granules. Interestingly, transformation of around 3.7mg TCE/gram suspended solid was found to be beneficial for phenol metabolism. However, transformation of around 6.6 mg TCE/ gram suspended solid was found to have negative effect on phenol degradation [72]. Zhang et al. have investigated possible mass transfer limitation involved in TCE degradation by phenol degrading aerobic granules. The authors have concluded that the aerobic granules of around 150 to 300 µm in diameter have shown maximum specific TCE degradation efficiency. Comparatively large granules with a diameter of around 700µm could achieve only 22% of the TCE degradation efficiency achieved by small microbial flocs [73]. Likewise, in another study Zhang et al. have concluded that co-metabolization of phenol and TCE could improve the integrity and settling ability of aerobic granules [74]. Pruden et al. have evaluated the application of aerobic fluidized bed reactor for BTEX (benzene, toluene, ethyl benzene and xylene) degradation. Activated carbon was used as substratum for microbial growth. The authors have reported that at an initial influent concentration of 2mg/L of each BETX compounds, nearly 99% removal of the mixture could be achieved [75]. Aerobic granulation technology is hardly evaluated for BETX degradation. In order to shed more light on wastewater treatment potential of aerobic granulation technology, a few new studies focused on BTEX degradation would be useful.

Concluding Remarks

Aerobic granulation technology is an effective technology for both municipal and industrial wastewater treatment. Various reports summarized in this article suggest that aerobic granulation technology has the potential to degrade and adsorb different pollutants ranging from textile dyes to phenol. However, biodegradation of toxic pollutant is still a relatively less explored area of aerobic granulation technology. Granule development is a relatively time consuming and complicated process and it could be a reason behind only a few reports available on toxic compound biodegradation by this technology. Rapid development of granules would be crucial for the success of this technology. Mass transfer resistance of the granules could be a problem for biodegradation of relatively hydrophobic pollutants such as petroleum hydrocarbons. Application of a suitable surfactant such as Tween 80 could be a solution of this issue. Aerobic granulation technology can maintain nearly 3-5 times more biomass concentration than conventional activated sludge process used for wastewater treatment. This is a big advantage of this technology. This advantage should be utilized to treat wastewater containing toxic pollutants. A relatively low wastewater: biomass ratio should be used to get maximum benefit of this advantage.

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