Optimizations on Supply and Distribution of Dissolved Oxygen in Constructed Wetlands: A Review

Huaqing Liu [a] *· Zhen Hu* [a] *· Jian Zhang* [a]*** *· Huu Hao Ngo* [b] *· Wenshan Guo* [b] *· Shuang Liang* [a] *· Jinlin Fan* [a] *· Shaoyong Lu* [c] *· Haiming Wu* [d]

[a] Shandong Key Laboratory of Water Pollution Control and Resource Reuse, School of Environmental Science & Engineering, Shandong University, Jinan 250100, PR China

[b] School of Civil and Environmental Engineering, University of Technology Sydney, Broadway, NSW 2007, Australia

[c] Research Centre of Lake Environment, Chinese Research Academy of Environmental Sciences , Beijing 100012, China

[d] College of Resources and Environment, Northwest A & F University, Yangling, Shaanxi 712100, China

**Corresponding author.* *Email address:* *zhangjian00@sdu.edu.cn*

Abstract

Dissolved oxygen (DO) is one of the most important factors that can influence pollutants removal in constructed wetlands (CWs). However, problems of insufficient oxygen supply and inappropriate oxygen distribution commonly exist in traditional CWs. Detailed analyses of DO supply and distribution characteristics in different types of CWs were introduced. It can be concluded that atmospheric reaeration (AR) served as the promising point on oxygen intensification. The paper summarized possible optimizations of DO in CWs to improve its decontamination performance. Process (tidal flow, drop aeration, artificial aeration, hybrid systems) and parameter (plant, substrate and operating) optimizations are particularly discussed in detail. Since economic and technical defects are still being cited in current studies, future prospects of oxygen research in CWs terminate this review.

Keywords：Constructed wetlands; Dissolved oxygen; Supply and distribution; Characteristics; Pollutants removal

1. Introduction

Constructed wetlands (CWs) are engineered systems which comprise water, substrates, soils, aquatic vegetations and microorganisms. These systems are designed and built to obtain wastewater (WW) treatment utilizing natural processes. Compared with traditional WW treatment technologies such as activated sludge process and biofilm process, CWs involve cheaper investment and operating costs. Additionally, the unexpected landscape value of wetlands is a great windfall in WW treatment. In the 1950s, Seidel (1961) carried out the first

CWs-based treatment of sewage in Germany. Since then, the application of CWs in WW treatment has been gradually implemented in Europe, North America, Australia, etc. In fact this technology is now widespread and has become popular in both developed and developing countries worldwide (Vymazal, 2010). The mechanisms for removing pollutants in CWs are rather complex, including not only physical processes like precipitation, filtration, sedimentation and volatilization but also biochemical processes induced by wetland plants and microorganisms. Generally, microbial degradation is accepted as the dominant process for removing organic matter, nitrogen, etc (Cui et al., 2013; Meng et al., 2014). A literature review shows that temperature, dissolved oxygen (DO), water quality and substrate are all influential factors for pollutants' degradation in CWs (Wu et al., 2015b). Among them, DO is a vital factor that could influence microbial activities and the efficiency required for pollutants removal.

The micro-biological degradation of organic matter takes place in both aerobic and anaerobic conditions. Aerobic degradation is suitable to treat low strength WW with high removal efficiency, while anaerobic degradation is usually applied in the treatment of high strength WW for the purpose of recovering resources (Chan et al., 2009). The former is more relevant to removing organic matter in CWs. It has been consistently documented in many reports that the higher oxygen content the faster organic matter can be degraded in CWs (Ong et al., 2010; Pan et al., 2015). On the other hand, organic degradation rather than nitrification prioritizes the use of oxygen. Consequently, most oxygen is preferentially consumed in organic matter degradation. The leftover of DO is usually insufficient for nitrification. Oxygen competition between organic matter and nitrogen becomes a critical problem which restrains the process of nitrification or even to a large extent total nitrogen (TN) removal (Hu et al., 2012). For phosphorus removal, compared with anoxic condition, phosphorus-accumulating bacteria can uptake phosphorus more rapidly utilizing oxygen as the electron acceptors in aerobic condition. Nevertheless, information of DO content influence on the removal of other pollutants such as heavy metals, sulfide, chloride, germs, pharmaceuticals and personal care products in CWs are rarely reported.

Many studies have contended that oxygen contents in traditional CWs are rather low, resulting in their relatively poor decontamination performance (Matamoros et al., 2008; Oon et al., 2015). Therefore, a variety of oxygen intensive technologies have been developed to enhance oxygen content in wetland beds (Li et al., 2014; Pan et al., 2015). However, high oxygen content does not equate to high pollutants removal efficiency. With the increase of oxygen supply, improvements in TN and total phosphorous (TP) removal have not been observed in some analyses (Jia et al., 2010; Ong et al., 2010; Wang et al., 2015). This phenomenon may well be explained by the fact that anaerobic state is also essential for microbial degradation. Optimization strategies should be developed to maintain alternating aerobic and anaerobic conditions (Jia et al., 2011). To date, a systematic statement and analysis on optimizations of oxygen supplies and distributions is still lacking.

Oxygen distribution characteristics in different types of wetlands are reviewed in this paper, with a specific emphasis on optimizations of DO in CWs for the past few years. Some future developments are suggested in the last part, aiming to provide references for wetlands research and engineering applications.

2. Supplies of oxygen in CWs

Although the mechanisms of oxygen supply in CWs are rather complex, it can be concluded that influent oxygen, plant oxygen release (POR) and atmospheric reaeration (AR) are three channels which supply most of the oxygen into wetland systems. Furthermore, many analytical methods are available to quantify oxygen supplies in wetlands, and even different methods are possible for just one process.

2.1 Influent oxygen

CWs influent often contains a certain amount of DO, which makes it one of the major sources of oxygen for CWs. The electrode method is an efficient tool, and is widely applied in measurement of oxygen for both influent and effluent. Table 1 summarized the characteristics of various WWs in full-scale CWs systems. To be convenient for comparison, in this paper, oxygen supply rate is described in g m^{-2} d^{-1}. As for the reports where the oxygen supply rate was not g m^{-2} d^{-1}, it was calculated based on conversion relationship of units. It can be observed from Table 1 that DO were generally much lower than BOD_5 in the influent, which means the large oxygen deficits for aerobic degradations of organic matter in most WW. Moreover, by stoichiometry, 1 g ammonia nitrogen consumes 4.57 g oxygen in the nitrification

2.2 POR

Oxygen produced by photosynthesis can be released from plant roots and leaves. Radial oxygen loss (ROL) is a complex process where oxygen goes through the aerenchyma from plant leaves and stems to plant roots, and is then released into the surrounding environment from the roots. However, in the strong oxygen consumption situation, plant roots have a tendency to reduce oxygen release, which directly limits the ROL process. As a result, the contribution of ROL to the wetlands DO is restricted (Austin and Nivala, 2009). Oxygen transfer rates vary with different plant species, light intensities, temperatures, etc. Lai et al. (2012) measured the ROL of 35 different wetland plant species utilizing the microelectrode method, and results indicated that oxygen release rates ranged between 0.1 and 2.2 g m^{-2} d^{-1}. Meanwhile, a positive correlation between ROL and removal rates of TN and TP was observed. Measurement method is another factor which had a big influence, by orders of magnitude, on the obtained ROL rate. Hence, some of the measurement methods that have been used for ROL estimation may be open to dispute. But on the whole, ROL rates of aquatic vegetation in most published research were less than 5.0 g m^{-2} d^{-1} (Table 2).

Apart from direct oxygen supply, ROL can improve decontamination indirectly by optimizing the microbial community structure in the substrate. Oxygen content is high in the plant rhizosphere due to the ROL effect, which can increase nitrifying bacteria activity. Conversely, denitrifying bacteria will prevail in the area away from the rhizosphere where only little oxygen exists. This anaerobic-aerobic scenario efficiently prompted TN removal of CWs. Subsequently, the effect of ROL would be underestimated if only taking the amount of oxygen supply into consideration.

Since leaves are the main place where photosynthesis and respiration occur, some submerged plants and phytoplankton in surface flow constructed wetlands (SF CWs) have a salient function of changing the oxygen environment through their leaves. Reeder, (2011) examined diurnal variation of DO concentration in various aquatic plants habitats in Beaver Creek Wetlands, Kentucky, USA and results indicated that DO was near zero at daybreak and rose to a saturated content past mid-day in submerged plants zones. In the meantime phytoplankton planted zones had less daily DO fluctuations due to the incomplete contact between leaves and water. Nevertheless, the intermitted alternating aerobic-anaerobic condition in day and night discounts the effect of pollutants removal in less microorganism existed free water body. Characteristics of DO induced by aquatic plants need to be further explored and applied.

2.3 AR

Hitherto, many mechanisms have been proposed to help understand the oxygen transfer process between air and water, such as molecular diffusion theory, two-film theory, etc. Oxygen transfer processes in CWs become more complex because of the influences of substrate as well as environmental factors including temperature and pressure (Boog et al., 2014). As shown in Table 3, the ARs of various types of CWs still have been quantified by some direct or indirect methods. Based on those reports, SF CWs and horizontal subsurface flow constructed wetlands (HSSF CWs) showed equivalent AR rates, and vertical subsurface flow constructed wetlands (VSSF CWs) always had more outstanding performance. Ye et al. (2012) calculated AR of a laboratory scale VSSF CW using mass balance method and claimed that its AR rate could reach as high as 469 g m^{-2} d^{-1}, and most of the oxygen in the wetland bed originates from the AR.

The contributions of the three oxygen supply channels have been quantitatively compared and depicted in Fig. 1. The minimum contribution rates of influent oxygen and ROL were negligibly low, and most of the corresponding data in the literatures of them were in the low level. The ranges from first quartile to third quartile of these data were calculated. The result was 0.02 to 0.38 g m^{-2} d^{-1} for influent oxygen and was 0.37 to 3.98 g m^{-2} d^{-1} for ROL. Nevertheless, the minimum values of AR showed better performance in all types of CWs, especially in VSSF CWs. These information indicate that AR served a major role on oxygen supply. On the other hand, the maximum oxygen contribution rate by AR in VSSF CWs was also significantly higher than that of influent oxygen and ROL, while the maximum ROL rates were higher than AR rates in SF CWs and HSSF CWs. Thus, the oxygen contributed by ROL should be emphasized under this circumstance.

3. Distributions of DO in different types of CWs

Apart from DO content, distribution of oxygen can also affect microbial activities and community structures, and further influence the efficiencies of pollutants removal to a large extent. Researches have shown that oxygen distributions vary significantly with different types of CWs. Therefore, details of oxygen characteristics based on wetland types are summarized in the following sections.

3.1 SF CWs

Microorganisms in the sediments play the major role on pollutants removal in SF CWs. However, microbial degradations processes are restricted as the reason of the limited attachment points for microorganisms. Relatively low oxygen consumption rates in the range of 0.08-0.15 g m^{-2} d^{-1} in SF CWs were reported

(Beutel, 2012; Kadlec and Wallace, 2009). As a result of atmosphere diffusion, SF CW forms an aerobic layer on water surface. When it is situated in the underlying water, consumed oxygen cannot be supplied sufficiently. Hence, oxygen content decreases with the depth of water and is at its smallest content at the sediments layer, where abundant microorganisms are existed. ROL provides a number of oxygen under the sediments layer. As pollutants can hardly permeate into the root layer, ROL influence little on nutrients removal and oxygen content will rise in this zone (Brix, 1997). In particular, as mentioned above, SF CWs would not constitute an oxygen-starved system in day-time if submerged plants and phytoplankton were taken into consideration. It was observed that DO was significantly increased in the system with submerged plants, which further improved the nutrient removal efficiency (Zhou et al., 2015). Despite all this, the finite oxygen is under-utilized in SF CWs because of the limited microorganisms in the free water.

3.2 HSSF CWs

HSSF CWs can enhance pollutants removal by making full use of microorganisms attached on the surface of soils, sands and plants roots. However, oxygen consumption rates were generally between 0.3-11.6 g m^{-2} d^{-1} in HSSF CWs, not as high as what we expected (Nivala et al., 2013). Compared with SF CWs, more than half of water surface area was reduced in HSSF CWs on account of the existence of non-submerged substances and leaf litter. Oxygen must pass through these obstacles before being diffused into water. Wind induced mixing which can accelerate the air diffusion process becomes non-operable, causing the oxygen diffusion rate of HSSF CWs to be generally lower than SF CWs.

As the reason of passive oxygen diffusion and oxygen release by roots, DO content in the upper zone in HSSF CWs is comparatively high. The lower zone always retains an anaerobic environment due to inadequate oxygen supply (Camacho et al., 2007). The HSSF CWs can take full advantages of ROL. The micro-environment of alternating aerobic-anaerobic formed in the plant roots zone supported the suitable habitat for aerobic, anaerobic, and facultative anaerobic microorganisms. Huang et al. (2013) also obtained that DO content in the upper layer was relatively high in summer and low in winter, which was mainly attributed to the plant activity variation influenced by temperature. In the horizontal flow direction, DO usually decreases to a low level within a short distance on account of more oxygen consumption in pollutants degradation than oxygen supply (Mburu et al., 2013).

3.3 VSSF CWs

WW feeds continuously and flows vertically from up to down of the substrates in original VSSF CWs. Since pollutants content is relatively high in influent, oxygen is consumed fast in the upper zone and a large oxygen concentration gradient forms in the surface water. According to Fick’s first law, the larger the concentration gradient, the faster the oxygen diffusion rate will be. Ye et al. (2012) found that more than 99.9% of DO in a VSSF CWs planted with reeds was supplied by air diffusion, with less than 0.1% of DO being attributed to influent oxygen and ROL. Furthermore, 50% of DO was consumed in the upper 10 cm of the system. Although the high oxygen consumption rate, DO content increased in the upper 10 cm and decreased gradually in the zone below 10 cm. Some air brought by the influent may well explain the DO increase in the top layer. Most oxygen was consumed by degraded organic matter in the upper 0-40 cm, and was mostly consumed by nitrification reaction in the lower part (40-140 cm). Along with the improved reaeration situation, degradation rate of organic matter and ammonia nitrogen were enhanced. Accordingly, most oxygen consumption rates reported were between 6-156 g m^{-2} d^{-1} in VSSF CWs (Nivala et al., 2013). Despite the improved reaeration, there is not enough oxygen being supplied while highly polluted WW is being treated. On the other hand, the denitrification process is limited to the high oxygen content situation, which can also reduce TN removal rate to some degree.

In recent years, the flow direction of some VSSF CWs have been designed from down to up. The overarching characteristic of this design is that oxygen cannot be supplied and sustained at a low level in the influent zone. As water flows, air diffusion and ROL supply oxygen to the system in the upper zone, which enhanced DO content. TN removal rate can be improved on account of the alternation of anaerobic and aerobic conditions. Moreover, the design can prevent mosquitoes, files and odor as well (Sirianuntapiboon et al., 2006).

4. Optimization of oxygen Supply and Distribution in CWs

In general, oxygen supply in traditional CWs is far from enough for degrading pollutants. As the contribution of influent oxygen and ROL are limited. AR is the most promising point on oxygen intensification. Moreover, the inappropriate DO distribution decreases the oxygen utilization efficiency of CWs, which further compromises the efficiency of the enhanced pollutants removal. Based on the pollutants removal mechanisms, supporting an alternation of aerobic and anaerobic environment is favorable to the removal of TN and TP

4.1 Process optimizations

Intensifications of AR are commonly realized through certain processes, which conclude tidal flow, drop aeration, artificial aeration and hybrid systems (see Table 4). The removal efficiencies of COD, ammonia nitrogen and TP in optimization utilized CWs were enhanced in most studies.

4.1.1 Tidal-flow CWs

In tidal-flow CWs, influent is controlled to ensure the wetland bed alternates between flood and drainage. As the substances can sufficiently contact with air in drainage period, oxygen supply could be intensified in the whole bed. In the following flood period, along with the consumption of DO, the wetland bed gradually turns into an anaerobic system. Reported reaeration rate of a tidal-flow CWs reached as high as 350 g m^{-2} d^{-1} (Wu et al., 2011b). The improved DO condition has a significant effect on microorganisms. Research has found that microbial activity in a tidal-flow CWs reached as high as 0.3 mg g^{-1}, which was three times that in HSSF CWs (Lv et al., 2013). Consistently, oxygen consumption rate was between 30-482 g m^{-2} d^{-1} in most cases (Nivala et al., 2013). Compared with traditional CWs, removal rates of organic matter, ammonia nitrogen and TP in in various types of wetlands were generally increased when tidal operated. However, TN removal rate fell in some reports as a result of the accumulation of nitrate nitrogen (Table 4).

4.1.2 Drop aeration

The method utilizing dropped water to enhance DO in the water system is called “drop aeration technology”. Air makes contact with water sufficiently while water drops down, and this can effectively promote the process of air-oxygen transfer to water. Furthermore, dropping water from a high attitude can produce waves on the water's surface, which benefits air diffusion at the same time. Application of "drop aeration technology" can efficiently enhance oxygen content in the wetland bed. Jie (2008) found that DO concentration was enhanced from 2.4 mg L^{-1} to 5.1 mg L^{-1} when the drop height was 2.5 m, and reaeration ability had a positive correlation with the drop height. Compared with traditional drop aeration, two-stage drop aeration is more efficient. Zou et al. (2012) discovered that two-stage drop aeration obtained 2.0-6.0 mg L^{-1} higher for DO than directly drop aeration when drop height was 1.0 m. Accordingly, BOD_5 removal rate improved from 8.1 g m^{-2} d^{-1} to 14.2 g m^{-2} d^{-1}. When the temperature is low, drop aeration may cause the water's surface to freeze. However, not only does this technology efficiently enhance DO in the wetland bed, it also exhibits great economic advantages in terms of low building and operating costs, convenient maintenance, etc. To summarize, drop aeration is an optional method to improve DO condition in no freezing condition.

4.1.3 Artificial aeration

As an effective device, aeration pump can be used to enhance DO content in all types of CWs. Oxygen content is rapidly enhanced by artificial aeration, and reaeration ability depends on the actual aeration situation. Corresponding to a high level of oxygen content, CWs operating artificial aeration showed high removal rates in organic matter and ammonia nitrogen as well as coliform bacteria (Wu et al., 2015a). The oxygen consumption rates were generally enhanced as well. The reported minimum oxygen consumption rate was below 30 g m^{-2} d^{-1}, and the maximum value could reach 4760 g m^{-2} d^{-1}, and this was largely depended on the contents of pollutants in the influent (Nivala et al., 2013). As oxygen consumed by pollutants degradation could be replenished rapidly with the role of artificial aeration, high oxygen consumption would be achieved in the treatment of high strength WW.

Compared to continuous aeration, more emphasis was put on intermittent aeration recently (Hu et al., 2016; Wu et al., 2016). Continuous aeration maintains a high level of oxygen which is conducive to aerobic degradation of organic matter and nitrification. However, an anaerobic environment which is necessary for nitrate nitrogen removal by denitrifying bacteria and energy storage of phosphorus-accumulating bacteria cannot be guaranteed. Intermittent aeration could not only supply sufficient oxygen at the aeration time but also provide an anaerobic environment at aeration intervals. Furthermore, the high operation cost of continuous aeration will be reduced while in the case of intermittent aeration. It has been found that TN removal rate reached as high as 90% in an intermittent aeration wetland when nitrogen loading rate was 46.7 g $m^{-2} d^{-1}$ (Hu et al., 2012). Besides, studies have found that the aeration position also had a great effect on spatial distribution of DO and pollutants removal efficiencies (Wang et al., 2015). Even though artificial aeration was proved to be successful in removing pollutants, the corresponding operational cost should be considered in any practical application. Austin and Nivala (2009) calculated that artificial aeration doubled the operational costs of tidal-flow CWs and halved energy consumption of activated sludge treatment system under the same treatment effect. Otherwise, the cost of periodic maintenance of aeration equipment and the cleaning or changing of aeration pipeline should be considered at the same time.

4.1.4 Hybrid systems

Hybrid systems are defined as combinations of difference types of CWs. A high pollutants removal rate can be obtained by utilizing the advantages and avoiding the disadvantages of each unit. Combined VSSF-HSSF CWs and integrated vertical-flow CWs are two commonly integrated systems which are conducted to realize better nitrogen removal. VSSF CWs have the advantages of high reaeration ability and strong shock resistance, while the reaeration ability of HSSF CWs is relatively poor. Nevertheless, HSSF CWs have the advantages of simple operation and maintenance. The combined VSSF-HSSF CWs can form an alternating aerobic-anaerobic condition system, which remarkably benefits TN and TP removal (Ávila et al., 2015). Integrated vertical-flow CWs divide VSSF CWs into two parts, forming aerobic down flow area and anaerobic up flow area (Hu et al., 2016). Compared with traditional VSSF CWs, an anaerobic up flow area is added in this kind of design. He et al. (2005) studied the nitrification and denitrification processes of an integrated vertical flow CWs. Results indicated that in accordance with DO content, nitrification rate and nitrifying bacteria decreased along with the flow, while denitrification rate and denitrifying bacteria decreased in turn. In addition, more complicated hybrid systems have been employed in WW treatment (Sharma et al., 2013). Compared to single type of wetland, all of these hybrid systems have shown their superiority in providing more diverse oxygen conditions and removing larger amounts of pollutants.

Broadly speaking, the combination of CWs and other WW treatment technologies belong to hybrid systems (He et al., 2016; Ju et al., 2014). Pretreatment of high concentration WW is essential before entering into CWs systems. Multiple pretreatment technologies have been applied in the literature, including solid separation, anaerobic digestion, etc (Wang et al., 2014a). The concentrations of pollutions will decline when these technologies are implemented. Thus, although influent DO of CWs may only be enhanced by aerobic pretreatment processes, the demand for oxygen in CWs could decline in every pretreatment system. Experiments were conducted to investigate the effect of anaerobic digester pretreatment on the performance of CWs (Álvarez et al., 2008). Results indicated that oxygen demand by pollutants degradation decreased to a large extent in CWs because the amount of organic matter declined following anaerobic pretreatment. In addition, the problem of clogging in CWs improved significantly when combined with these pretreatment technologies.

4.2 Parameter optimizations

It is known that parameter control is an essential aspect of both scientific research and engineering applications. Parameter optimizations in CWs can be further divided into plant, substrate and operation optimizations (Sultana et al., 2015). As shown in Table 5, DO changes regularly according to different parameter settings. Even though positive correlations between DO content and pollutants removal rates are not found in all cases mainly due to other influential factors, DO optimizations by parameters control can be achieved.

4.2.1 Plant optimizations

Selection of plant species has long been valued by researchers in wetland construction. Since the diversities of plants uptake, ROL and roots structure greatly influenced microbial activity and community structure, the removal efficiencies of pollutants for various habitat plants were distinct in CWs (Chang et al., 2012). From the perspective of oxygen contribution, aquatic plants with high density, strong ROL ability and extensive root systems are proposed in plant selection (Zheng et al., 2016). In addition, with reference to the role of leaf photosynthesis and respiration, significant differences of oxygen distribution characteristics were reported in emergent, submerged and floating plants habitat systems (Reeder, 2011). More researches should be carried out on the utilization of oxygen from leaf photosynthesis in SF CWs.

The density of plant also has a significant impact on the decontamination effect. Ibekwe et al. (2007) investigated six wetland units in a SF CW dominated by cattail and reed at a ratio of 1:1 with different plant densities. Results indicated that microbial community diversity and nitrate removal rates were much higher in units with 50% plant cover than those with 100% plant cover. It was explained that the 100% plant cover wetland unit had a low DO content due to the weak oxygen diffusion and increased detritus created by the excessive plant density. Information concerning plants density optimization in subsurface flow CWs is rare in the literature. Commonly, the greater the plant density the larger role optimization plays. Nevertheless, a plant density of less than 80% coverage is recommended for sustainable development (Wu et al., 2015b).

4.2.2 Substrate optimizations

Wetland substrate provides not only physical support for aquatic vegetation, but also surfaces for pollutants attachment and microbial activity. Hitherto, a great many media species were experimented with to attain better decontaminant performance. Adsorption capacity, microbial activity and diversity differ according to substrate types. Furthermore, Shuib et al. (2011) compared two parallel HSSF CWs systems filled with zeolite and gravel, respectively. A significant difference of DO content in effluent was observed in the monitoring lasted over a year. Nevertheless, the oxygen adsorption mechanism of various substrates in CWs is still not fully understood.

Substrate depth is another fact influencing DO distribution in CWs. Commonly, when substrate depth increases, more space is produced for microbial activities. Pollutant removal rates via microbial degradation will be enhanced as shown in Table 5. However, García et al. (2004) evaluated the effect of substrate depth on removal of pollutants in HSSF CWs. The results indicated that shallow bed (27cm) functioned much better in terms of decontamination compared to a deep one (50cm). This phenomenon was attributed to the DO distribution of HSSF CWs. As DO content in the upper zone is relatively high, most microbial degradation reaction occurred in the high oxygen content zone in the shallow bed. Therefore, greater efficiencies in pollutants removal were observed in lower substrate depth scenarios. To strike a balance between treatment space and DO content, there may be an ideal depth for water purification.

4.2.3 Operation optimizations

As a semi-landscape and semi-water-treatment system, CW is an ecosystem comprising rich biological diversity and many functions. HRT of WW in CWs is generally much longer than that in other systems. Many studies indicated DO content falls when HRT increases (Shuib et al., 2011; Xiao et al., 2010). Less supply of influent DO in long HRT situation may reasonably explain this phenomenon. Conversely, DO content could maintain a comparatively high level in short HRT situation, which favors microbial degradation of organic matter and ammonia nitrogen. The disadvantage is that of comparably poor quality effluent on account of inadequate contact time for removing pollutants. Therefore, on the basis of satisfying emission standards, a short HRT is more profitable from the perspective of using oxygen.

With reference to tidal-flow CWs, the control of flood period and drainage period is critically important to DO research. Superiority of oxygen condition optimization is highlighted by constraints of flooded time. Hu et al. (2014) studied nitrogen removal under different flood and drain ratios in tidal-flow CWs and their results confirmed that removal efficiency of ammonia nitrogen and TN were enhanced when the flood and drain ratio decreased. However, when reduced the carbon source, TN was dramatically decreased due to the accumulation of nitrate nitrogen. As it can be indicated, for the purpose of TN removal, high flood and drain ratio of tidal-flow CWs is more suitable to treat high C/N WW, and vice versa.

Normally, the higher concentration of the biodegradable pollutants (e.g., biodegradable organic material and Kjeldahl nitrogen) in the influent, the faster oxygen will be consumed. Consequently, DO content in CWs is extremely low in the treatment of high strength WW. Although the adverse effects of specific pollutants, for example, anaerobic fermentation products, on wetland ecosystem have not been evaluated systematically, direct treatment of high strength WW using a single type of CWs is not advised. In addition, under a high hydraulic loading rate, the result may be poor quality effluent or blocking. Considering the increasingly stringent emission standards, influent pollutants concentration should be restricted moderately. Combined with a practical application, pretreatment of high strength WW is necessary before sending this WW into

CWs.

5. Challenges and future prospects

The accurate determination of oxygen supply rates in CWs is essential for its design and operation. However, it could be concluded from the remarkable gap of values in Table 1 to Table 3 that disputes existed in the present methods. The suggestions to resolve this problem are as follows. Firstly, more factors such as plant adsorption and anaerobic degradation should be taken into account for some existing methods like mess balance, model simulation, etc. Accuracy validation is essential before these methods can be applied. Secondly, standard operating instructions should be established and popularized for some complex experimental methods such as isotope analysis and gas tracer method. In general, building the reliable oxygen measurement methods in CWs is a basic task ahead for oxygen optimizations.

After decades of practice, CWs were widely recognized as effective WW treatment microcosms. The oxygen optimization technologies in CWs presented in this review carried good potentials for purification processes. However, some of these oxygen intensifying methods such as tidal-flow, drop aeration and artificial aeration brought new problem of increasing operating cost. These kinds of technologies can well be applied in some wetland landscapes. From the perspective of economy, the hybrid systems as well as parameters controls are advised by their advantages in oxygen optimization and pollutants removal without operating cost increase. For the treatment of high strength WW, reducing the oxygen consumption demand by pretreatment processes rather than optimizing oxygen environment in situ is more feasible. Hence, the combination of CWs and low-cost WW pretreatment technologies requires more development in future studies.

Apart from oxygen, some irons can substitute as electron acceptor for effective degradation of pollutants. In anammox process, electrons are transferred from ammonia nitrogen to nitrite under the role of microorganisms. Ammonia nitrogen will be directly translated to harmless nitrogen gas in this process. Moreover, it emerged that ammonia nitrogen can be oxidized to nitrite by utilizing ferric iron as electron acceptor. Through these processes, oxygen demand will be reduced. In addition, some aerobic reactions like nitrification process will be achieved in anaerobic condition. In consideration of the prevailing anaerobic environment in wetland substrate, it is quite meaningful if these kinds of anaerobic degradation were developed further and implemented in CWs.

From another point of view, the electron acceptor role of oxygen can be replaced by anode of microbial fuel cells (MFCs) or microbial electrolysis cells (MECs). It has been concluded that pollutants removal efficiencies of CWs could be significantly improved by incorporating MFC technology. Meanwhile, energy extraction form WW could be achieved in CW-MFC systems (Doherty et al., 2015). With polarized electrode as electron accepter, the direct transformation from ammonia nitrogen to nitrogen gas was realized on the anode of a MEC system. Denitrification rates could be largely enhanced with the cathode as the electron donor (Zhan et al., 2012). Incorporation of these microbial electrochemical technologies may help intensify TN removal in CWs with no-secondary pollution and low energy consumption.

6. Conclusions

Based on oxygen supply characteristics, the current review illustrated the deficiencies of insufficient oxygen supply and unreasonable DO distribution in traditional CWs for WW treatment. To address these situations, several processes and parameters optimizations have been conducted. Through these optimizations, improved DO conditions and increased water purification efficiencies have been obtained. However, technical and economic limitations still exist according to current studies of DO optimizations in CWs. More systematic studies are necessary for better applications to be developed and implemented in the field.

Acknowledgements

This work was supported by National Natural Science Foundation of China (No. 21307076, No.41305124& 21507072), Fundamental Research Funds of Shandong University (No. 2014TB003&2015JC056), and Shandong Provincial Natural Science Foundation (ZR2015PB001).

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Figure Captions:

Fig. 1. Quantitative comparison of oxygen contributions of influent oxygen, ROL and AR (Values of Influent O_2, ROL and AR were adapted from Table 1, Table 2 and Table 3, respectively. The whiskers show maximum and minimum values and the solid dots represent the mean value. The bottom and top of the box frame show first quartile and third quartile, respectively.).

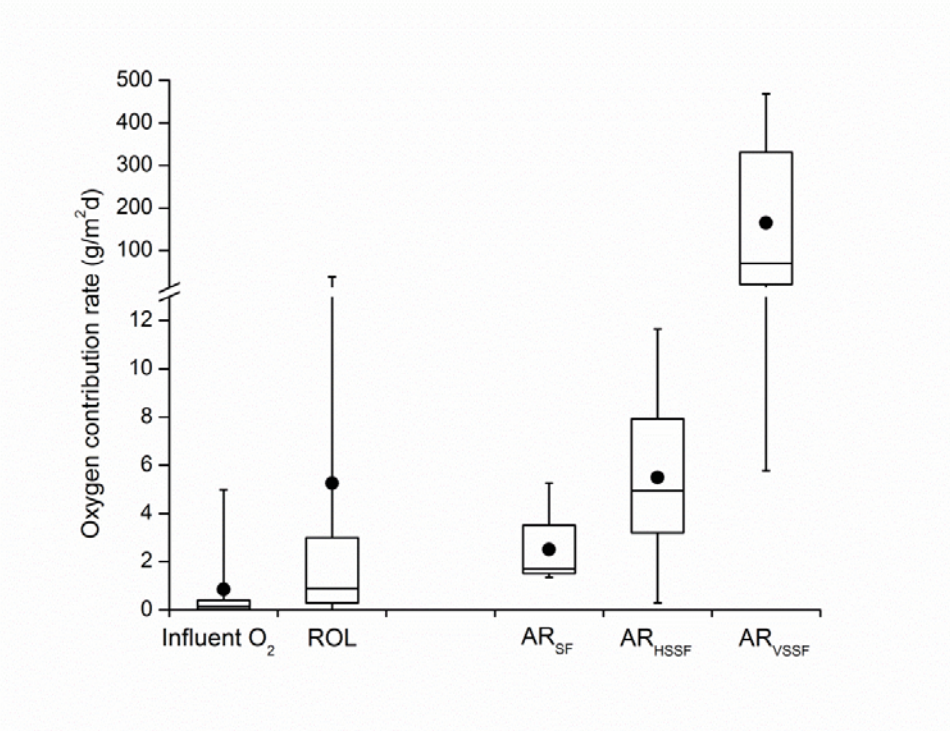

Fig. 1. Quantitative comparison of oxygen contributions of influent oxygen, ROL and AR (Values of Influent O_2, ROL and AR were adapted from Table 1, Table 2 and Table 3, respectively. The whiskers show maximum and minimum values and the solid dots represent the mean value. The bottom and top of the box frame show first quartile and third quartile, respectively.)

Table 1 Characteristics of full-scale CWs in the treatment of various WWs.

No.	WW type	CW	DO			BOD_5			NH_4-N			References
		area (ha)	In (mg/L)	In (g/m^2d)	Out (mg/L)	In (mg/L)	Out (mg/L)	%	In (mg/L)	Out (mg/L)	%	
1	Secondary municipal effluent	1.00	1.2	0.012	7.8~8.9	10~11	4~30	n.r.~63	37.8~61.0	3.0~15.3	79~94	(Matamoros et al., 2008)
2	Livestock WW	0.60	2.5	0.025	1.6	104~442	24~141	25~83	5.1~366.0	2.2~221.0	20~60	(Knight et al., 2000)
3	Piggery WW	0.01	0.6	0.023	0.3	1126 [a]	235 [a]	79	390	145	63	
4	Tannery WW	0.01	1.4	0.056	1.3	45	12	73	6.7	1.8	73	(Calheiros et al., 2012)
5	Shrimp aquaculture WW	7.70	0.8	0.141	1.9	1.7	1.5	15	0.4	0.9	n.r.	(Tilley et al. 2002)
6	Domestic WW	0.09	5.0	0.371	6.3	102	18	82	44.0	22.4	49	(Arroyo et al., 2010)
7	Winery WW	0.04	2.3	0.405	1.4	22~2950	5~1893	45~95	0.1~171.0	0.3~52.2	n.r.~69	(Serrano et al., 2011)
8	Eutrophic lake water	0.01	7.8	4.992	1.9	7	4	42	1.6	0.9	45	(Li et al., 2008)

n.r., no removal was observed.

[a] COD values instead of BOD_5.

Table 2 ROL characteristics of wetland plants.

No.	Methods	Plant Species	Radial oxygen loss (g/m^2d)	References
1	Closed chamber method	*Scirpus validus*	0.0023	(Bezbaruah & Zhang, 2005)
2	Closed chamber method	*Phragmites australis*	0.14	(Wu et al., 2014)
3	Model simulation	*Typha orientalis*	0.45	(Mburu et al., 2012)
4	Model simulation	*Schoenoplectus*	0.94	
5	Model simulation	*Carex rostrata*	1.91	
6	Model simulation	*Phragmites australis*	3.94~25.20	(Wu et al., 2014)
7	Stoichiometry	*Phragmites australis*	0.85	(Choi et al., 2006)
8	Microelectrode	35 plant species	0.1~2.2	(Lai et al., 2012)
9	Isotope analysis	*Phragmites australis*	4.1	(Wu et al., 2011a)
10	Mass balance method	*Acorus calamus*	38.4	(Dong et al., 2011)

Table 3 AR characteristics of various types of wetlands.

No.	CW type	Scale	Area (m^2)	WT [a]	Method [b]	AR rate (g/m^2d)	References
1	SF	Lab	1.08	S	CC	1.36~1.76	(Wu et al., 2001)
2	SF	Full	805	M	MB	1.66~5.27	(Gasiunas, 2011)
3	HSSF	Lab	0.06	W	GT	0.3~3.2	(Tyroller et al., 2010)
4	HSSF	Full	n.a.	M	MB	3.87~11.66	(Gasiunas, 2011)
5	HSSF	Lab	1.08	S	CC	6.01~7.92	(Wu et al., 2001)
6	VF	Full	1500	M	MB	5.77~18.45	(Gasiunas, 2011)
7	VF	Lab	0.65	T	MB	24~213	(Saeed et al., 2012)
8	VF	Lab	0.75	D	MB	469	(Ye et al., 2012)

n.a. no data was available.

[a] WT represent WW type including synthetic WW (S), secondary municipal effluent (M), tap water (W), domestic WW (D), and tannery WW (T).

[b] Measurement method including closed chamber method (CC), mass balance method (MB), gas tracer method (GT), and ideal gas law (IG).

Table 4 Increase of pollutants removal ratios compared processes optimization utilized CWs with conventional CWs.

Optimize methods	CW type	Scale	Area(m^2)	WT [a]	ΔCOD (%) [b]	ΔNH_4^+-N (%) [b]	ΔTN (%) [b]	ΔTP (%) [b]	References
Tidal flow	VSSF	Lab	0.24	S	3.7	30.8	-20.5	4.5	(Jia et al., 2010)
	VSSF	Lab	0.24	S	4.6	27.4	-10.9	4.7	(Jia et al., 2010)
	SF	Lab	0.18	S	-1.8	-2.4	-2.0	n.a.	(Jia et al., 2011)
	SF	Lab	0.18	S	3.7	30.8	-20.4	n.a.	(Jia et al., 2011)
	HSSF	Lab	0.72	S	0.7	23.0	n.a.	29.1	(Zhang et al., 2012)
	HSSF	Lab	0.72	S	0.5	13.7	n.a.	24.1	(Zhang et al., 2012)
Drop aeration	HSSF	Lab	0.12	D	35.0	n.a.	20.0	10.0	(Jun et al., 2012)
	VSSF	Lab	0.07	S	n.a.	24.1	n.a.	n.a.	(Chen Mingli, 2009)
Artificial aeration	VSSF	Lab	0.10	S	4.0	52.0	3.0	-3.0	(Ong et al., 2010)
	VSSF	Lab	0.10	S	12.0	75.0	5.0	3.0	(Ong et al., 2010)
	VSSF	Lab	0.10	S	14.0	54.0	9.0	2.0	(Ong et al., 2010)
	VSSF	Lab	0.03	S	12.7	67.1	46.8	35.9	(Wu et al., 2015a)
	VSSF	Lab	0.03	S	24.9	70.7	52.4	36.2	(Wu et al., 2015a)
	VSSF	Lab	0.03	S	28.3	75.7	59.9	35.8	(Wu et al., 2015a)
	VSSF	Lab	0.03	S	34.0	78.1	62.7	39.0	(Wu et al., 2015a)
Hybrid system	VSSF-HSSF	Full	50-300	W	16.9	24.6	n.a.	n.a.	(Serrano et al., 2011)
	VSSF-HSSF	Full	371-229	D	5.8	22.7	26.0	18.6	(Ávila et al., 2015)

n.a. no data was available.

[a] WT represent WW type including synthetic WW (S), domestic WW (D), and winery WW (W).

[b] $\Delta R = R_P - R_T$ Where ΔR is increase of pollutants removal ratio, %; R_P is pollutants removal ratio of processes optimization utilized CWs, %; R_T is pollutants removal ratio of traditional CWs, %.

Table 5 Characteristics of COD, TN removal rates and DO content with different parameter settings.

Controlling factor	Parameter setting	CW type	Scale	Area(m^2)	WT [a]	DO (mg/L)	COD removal (g/m^2d)	TN removal (g/m^2d)	TP removal (g/m^2d)	References
Plant species	*Cattail & A. donax*	VSSF	Lab	1.00	S	0.8	44.3	1.3	0.39	(Chang et al., 2012)
	Canna & pontederia	VSSF	Lab	1.00	S	0.9	46.4	1.1	0.39	
Substrate depth	80cm	VSSF	Lab	0.10	S	2.7	47.7	5.9	0.53	(Wang et al., 2014b)
	60cm	VSSF	Lab	0.10	S	4.6	41.8	6.0	0.56	
	40cm	VSSF	Lab	0.10	S	5.5	35.4	5.8	0.39	
Substrate type	Zeolite	HSSF	Lab	0.36	S	2.0	52.8	11.7	n.a.	(Shuib et al., 2011)
	Gravel	HSSF	Lab	0.36	S	3.1	57.8	1.4	n.a.	
Hydraulic retention time (HRT)	35h	VSSF	Lab	1.00	D	2.4	n.a.	1.4	0.11	(Xiao et al., 2010)
	23h	VSSF	Lab	1.00	D	3.0	n.a.	1.1	0.18	
	17h	VSSF	Lab	1.00	D	3.5	n.a.	1.9	0.26	
Flood and drain ratio	13.5	VSSF	Lab	0.01	P	n.a.	148.7	11.2	3.70	(Hu et al., 2014)
	3.8	VSSF	Lab	0.01	P	n.a.	133.3	17.6	1.85	
	1.9	VSSF	Lab	0.01	P	n.a.	202.8	23.9	4.53	
Pollutants load	COD/TN/TP=15.8/1.5/0.1 g/m^2d	VSSF	Lab	0.03	S	0.4	13.5	0.6	0.07	(Wu et al., 2015a)
	COD/TN/TP=27.7/2.8/0.2 g/m^2d	VSSF	Lab	0.03	S	0.2	20.4	1.0	0.14	

n.a. no data was available.

[a] WT represent WW type including synthetic WW (S), domestic WW (D), and piggery WW (P).

- Oxygen supply and distribution characteristics in different types of CWs are analyzed
- Optimizations of DO in CWs for decontamination purpose are summarized and discussed.
- Atmospheric reaeration plays an important role on oxygen intensification.