New insights for enhancing the performance of constructed wetlands at low temperatures

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Abstract： Constructed wetlands (CWs) have been widely utilized for various types of wastewater treatment due to their merits, including high cost-effectiveness and easy operation. However, a few intrinsic drawbacks have always restricted their application and long-term stability, especially their weak performance at temperatures under 10°C (low temperatures) due to the deterioration of microbial assimilation and plant uptake processes. The existing modifications to improve CWs performance from the direct optimization of internal components to the indirect adjunction of external resources promoted the wastewater treatment efficiency to a certain degree, but the sustainability and sufficiency of pollutants removal remains a challenge. With the goal of optimizing CW components, the integrity of the CW ecosystem and the removal of emerging pollutants, future directions for research should include radiation plant breeding, improvements to CW ecosystems, and the combination or integration of certain treatment processes with CWs to enhance wastewater treatment effects at low temperatures.

Keywords: *Constructed wetland; low temperature; performance enhancement; ecosystem; radiation breeding.*

1. Introduction

In the narrow sense, wetlands are ecotones with high biodiversity that exist between terrestrial ecosystems and aquatic ecosystems, and their surfaces are wet or often accumulate water (Junk et al., 2013). The global area of wetlands estimated from the Ramsar Convention and United Nations Environment Program is between $1.52*10^9$ hm^2 and $1.62*10^9$ hm^2 (Davidson et al., 2018; Gong et al., 2010; Zheng et al., 2015). As one of the three major ecosystem types worldwide and known as being "the earth's kidney" (Janse et al., 2019), the wastewater could be purified in wetlands through a series of processes (sediment entrapment, nutrient absorption, and toxic substance degradation) based on the synergistic action of microbe, soil, and plant. Moreover, on the one hand, the wetland is the source of water storage, and provides natural resources such as peat, reed, and medicinal materials in human production and life. On the other hand, it has the excellent characteristic of genetic diversity and provides a suitable habitat and breeding area for aquatic animals and plants (An and Finlayson, 2018). The function of the wetland ecosystem at the evaluation level of the ecological environment and social economy creates an annual value up to 14,000 dollars/hectare, which is 7 times and 160 times the value of the tropical rain forest and the farmland ecosystem, respectively (Davidson et al., 2019; Junk et al., 2013; Kumar and Dutta, 2019; Moomaw et al., 2018). However, the Wetland Extent Trends index have suggested that the natural wetlands declined globally on average by about 30% between 1970 and 2008 (Davidson and Finlayson, 2018; Dixon et al., 2016). Based on imitation of the structure and function of natural wetlands and mitigation of wetland destruction (Davidson, 2014; Xu et al., 2019), constructed wetlands (CWs) concentrated on wastewater treatment have received increasing attention in recent decades (Arden and Ma, 2018; Feng et al., 2019; Wang et al., 2018).

CWs are an integrated ecosystem for efficiently removing pollutants by synergetic processes, including plant uptake, microbe assimilation and substrate adsorption (Wu et al., 2015). The advantages of high cost-effectiveness and easy operation make CWs appropriate for wastewater treatment in regions without public wastewater systems or regions that are economically underdeveloped (Wu et al., 2015; Wu et al., 2018). In China, the construction area of CWs (674.59 million hectares in 2014, accounting for 12.63% of the total wetland area in China) based on the local geographical conditions, climatic factors, and ecological landscapes have developed rapidly in recent years (**Fig. 1**) (Zhou et al., 2014). Particularly due to their low construction costs (one-third to one-half the cost of a wastewater treatment plant) and operation maintenance costs (0.05-0.2 yuan/ton wastewater, compared to 0.7-1.5 yuan/ton wastewater in a wastewater treatment plant) (Yu et al., 2018), CWs play an irreplaceable role in the wastewater treatment and economic development of the developing countries like China and India (Gorgoglione and Torretta, 2018; Semeraro et al., 2015).

According to an analysis of the distribution of these wetlands, however, they are mainly located in the mid-low latitudes, and only a small number of wetlands are located in the high latitudes (An and Finlayson, 2018). Because of the ecological attributes of

CWs, climate conditions have always been a significant factor in the unreliable water treatment of CWs (Hwang and Oleszkiewicz, 2007; Stottmeister et al., 2003; Xie et al., 2003; Zietzschmann et al., 2015). Previous studies have shown that the removal efficiencies of ammonia nitrogen (NH_4^+-N), total nitrogen (TN) and total phosphorus (TP) at low temperatures were reduced by 15%, 45% and 16%, respectively, compared to those observed at the optimal temperature (25°C) (Song et al., 2006; Taylor et al., 2011; Zhao et al., 2019). When microbial activity and plant growth are affected by low temperatures, the processes of pollutant transformation and mass transfer in CWs are retarded, so the declining efficiency of the ecosystem function and the insufficient performance period limit the removal efficiency of CWs as well as their promotion and application (Dixon et al., 2016). Therefore, it is necessary to promote the construction value of CWs by achieving year-round stable operation performance, and enhancing the performance of CWs at low temperatures is undoubtedly a significant issue demanding a prompt solution.

This paper elucidated the mechanisms affecting the operation performance of CWs and summarized the existing strategies for the optimization of internal components and the improvement of external operation conditions of CWs in order to enhance wastewater treatment at low temperatures. Meanwhile, the new pathways necessary and helpful for future applications of CWs at low temperatures were discussed.

Fig. 1 The distribution of CWs in administrative regions of China (The site and size of

circles indicates provincial capital and area respectively).

2. Impact of low temperatures on constructed wetlands performance

2.1. Pollutant removal pathways of constructed wetlands

The removal pathways (**Fig. 2**) of common pollutants (nitrogen and phosphorus) in CWs were mainly attributed to the processes of plant uptake, substrate adsorption, and microbe assimilation, which occupied different proportions in pollutants removal due to their respective removal mechanisms (Coban et al., 2015). However, at low temperatures, these processes were affected directly or indirectly by a variety of variables including the oxygen transfer efficiency of the plant, the adsorption and sedimentation velocity of the substrate, the microbial metabolism rate, the operational mode, and the dissolved oxygen concentration. Although low temperatures may result in a seemingly favorable change in CWs like the increase of dissolved oxygen, various routes of pollutant removal in CWs were adversely affected by low temperatures (Blanco et al., 2016).

Fig. 2 Main pathways of pollutants removal in CWs.

(1) OP: Organophosphorus; DP: Dissolved phosphorus; IP: Inorganic phosphorus; PP: Particulate phosphorus. (2) Account for the proportion of pollutants removal: ① 5.4-20.1% N, 4.8-22.3% P; ② 4.5-8.3% N, 36.2-49.7% P; ③ 89-96% N.

2.2. Impact of low temperatures on microbes

As the major biological community responsible for pollutant degradation and assimilation (Petersen et al., 2015), microbe was perceived as making great contributions to CWs; the transformation processes of organic matter and nitrogen compounds are primarily completed in the aerobic and anaerobic zones of CW wastewater via microbial metabolic activities (Bai et al., 2014; Faulwetter et al., 2009). However, (1) at low temperatures, the microbial activity and metabolic rate in the CW systems were reduced, which seriously impeded the heterotrophic bacteria in decomposing organic pollutants (Lin et al., 2015); (2) the reaction efficiency of nitrification (optimal temperature of 20-30°C) dropped rapidly while the temperature was 15°C, and the reaction almost stopped at 5°C (Jurado et al., 2009); and (3) simultaneously, as the most effective way to denitrify (85% of nitrogen) in CWs, the reaction rate of denitrification (optimal temperature of 5-40°C) also decreased at 15°C, thus resulting in a decrease in the operational efficiency of CWs (Du et al., 2018).

2.3. Impact of low temperatures on plants

Plant was an indispensable component in CW treatment, as they could utilize the nitrogen and phosphorus nutrients from wastewater for their own growth and conduct the plant-mediated oxygen transfer for organic carbon oxidation and nitrification processes (Březinová and Vymazal, 2015). In general, the temperature of plant growth was in the range of 4-36°C, while the fiducial temperature was 5-10°C (Huang et al., 2013). However, (1) the metabolic processes of plants, such as photosynthesis, respiration and transpiration, were weakened at low temperatures, which affected the synthesis and transport of organic matter (Van de Moortel et al., 2010); (2) the oxygen supply to plants was restricted at low temperatures, and the voids connected with substrate and air affected the radial oxygen loss because of the decreasing root activity, thus resulting in a reduction in reoxygenation, which then affected the assimilation of nitrogen pollutants (Ren et al., 2016); and (3) since soil and air temperature were also directly influenced at low temperatures, the amounts of available nutrients, such as ammonium, nitrate and phosphate, that could be directly adsorbed or assimilated by plants from the CW soil were reduced dramatically. Moreover, the ice crystals formed in dormant plants caused withering and even death at extreme low temperatures, after the processes of plasmalemma breakdown and protein inactivation and denaturation, therefore reducing the removal performance of the plant (Stottmeister et al., 2003).

2.4. Impact of low temperatures on the substrates

The substrate, a crucial parameter in CW treatment, furnished most of the physical, chemical and biological reaction interfaces in CWs (Zhou et al., 2018). Commonly used types of substrate in CWs were including natural materials, industrial waste, and synthetic materials (Yang et al., 2018). Not only did substrate provide a stable attachment surface for the microbe growth and a growing medium for aquatic plants but they also furnish the high hydraulic conductivity avoiding short-circuiting of wastewater (Stefanakis and Tsihrintzis, 2012). The nonbiological interactions between the phosphorus and the substrate, such as the process of chemical deposition between phosphate and cation (e.g., Mg^{2+}, Ca^{2+}, and Al^{3+}), was deemed to be the main mechanism of phosphorus removal (36.16-49.66%) in CWs (Kivaisi, 2001).

Akratos and Tsihrintzis (2007) indicated that the mean PO_4^{3-} and TP removal efficiencies under 15°C were decreased by 28.5% and 28.3%, respectively, compared with those above 15°C. Citing zeolite as an example, the temperature affected both phases (internal and external diffusion phases of particles) of substrate adsorption (Yang et al., 2018). During the adsorption process at low temperatures, the ability of phosphorus in wastewater to overcome the liquid film resistance of the zeolite surface was weakened, which effectively migrated the phosphorus along the pores of zeolite into the inside, thereby reducing the surface area of the adsorption site (McCarey et al., 2004; Postila et al., 2015). Moreover, external low temperatures reduced the adsorption capacity of the wetland bed because the process of phosphorus adsorption was an endothermic reaction. The viscosity of wastewater increased and the rate of water molecules entering the plant root zone decreased, resulting in a decline in oxygen transfer efficiency and in physiological activity of plant and microbe (Pang et al., 2015). However, Sani et al. (2013) showed that phosphorus removal did not depend on the temperature, based on seasonal variations under changes to hydraulic retention time (HRT) and loading rate, because physical-chemical reactions, rather than biological action, were principally responsible for TP removal. It should be clarified that the particular phosphorus did not dissolve well in the substrates that were not saturated by phosphorus or other compounds competing of adsorption sites. Likewise, Jenssen et al. (1993) ascribed the 98% phosphorus removal to the adsorption force of the porous medium and the iron oxides in soil.

3. Modifications to enhance constructed wetlands performance at low temperatures

Aiming to improve the low removal rate of CWs at low temperatures, researchers have carried out many modifications based on the internal space components (microbial activity, plant uptake, substrate addition) or external operational factors (heat loss, operating situation, and dissolved oxygen) of CWs in recent years in response to the effects of cold stress on CW performance (**Fig. 3**). Direct modifications to the CW components included the utilization of microbial inoculum and bioturbation for the promotion of microbial activity (bio-augmentation), seasonal planting collocation systems and cold-resistant plants to promote plant uptake (plant configuration), and supplements of plant straw and plant-based biochar to create a favorable anaerobic environment and encourage ion exchange (substrate property). Indirect modifications based on the CW operation included adding mulch material and building greenhouses (isolation and heat preservation), imposing batch-type flow for the alternation of aerobic-anaerobic treatment conditions and adjusting HRT/ hydraulic loading rate

(HLR) parameters (treatment condition), and for improving dissolved oxygen concentration (artificial aeration).

Fig. 3 Modifications were responding to the cold stress on CW performance at low temperatures.

3.1. Direct modifications

3.1.1. Bio-augmentation

Microbial degradation was the main route to removing pollutants in CWs (Wood et al., 1999). However, the growth of microbes in CWs was very restricted at low temperatures (Jurado et al., 2009; Liu et al., 2017). Xu et al. (2018) found that *Psychrotrophs* were adapted to domestic wastewater due to their better adaptation for temperature fluctuations. Aiming to attain the approximate degree of microbial metabolism compared with that under normal temperatures in CWs at low temperatures, Xu et al. (2017) revealed that the *Pseudomonas putida* Y-9 screened from long-term flooded paddy soil (**Table 1**) had an excellent denitrification capacity (1.60 mg nitrate nitrogen (NO_3^--N)/L/h, 1.83 mg nitrite nitrogen (NO_2^--N)/L/h) for treating wastewater at 15°C, especially the wastewater containing high concentrations of nitrogen. Immobilized microorganism technology was also a way to degrade organic matter by increasing redox potential through cold-adapted bacteria placed in stable carrier material

(Ben et al., 2009; Isaka et al., 2012; Zhang et al., 2011), but the removal rate by directly adding microbes to CWs would be limited by the decomposition of the gelatin and the adaptability of the bacterial strain itself. Bio-augmentation was an effective alternative, as it provided the microbe with particular functions at a sufficient amount (Yeh et al., 2010). Compound microbial agents formed a new microflora balance in situ by transforming the intrinsic species homogeneity of nitrogen-related bacteria in the soil microbial community structure of CWs (Zhao et al., 2016). The addition of multichannel biological fillers including salt-tolerant bacteria, photosynthetic bacteria, low-temperature dephosphorization and nitrogen-removal bacteria showed the 35.4% NH_4^+-N, 33.6% TN, 28% TP, and 30% chemical oxygen demand (COD) removal efficiencies in surface-flow CWs under the double stresses of high salt and low temperature. Although the microbial richness of the system was reduced, the major microbial species present were not significantly different (Duan et al., 2016).

The nitrogen and phosphorus removal of CWs with earthworms were 2-5% and 12% higher than those without earthworms, respectively (Li et al., 2011). It was reported that the microbial-earthworm ecofilters (MEEs) system had the advantages of a microporous structure, and higher porosity and specific surface area, and could be applied to CWs for COD removal and denitrification at low temperatures (Huang et al., 2014; Wang et al., 2011; Zhao et al., 2012; Zhao et al., 2014). In terms of the economic effectiveness, MEEs had a lower operational and maintenance cost in treating wastewater as no requirements on experienced labor and a little energy supplement on pumps. Meanwhile, as a feasible option with economy for earthworm breeding, MEEs could create the value up to almost $ 40 (1,000 earthworms) in market of Australia (Sinha et al., 2008). Even more important, the total suspended solids and COD could be removed more efficient in MEEs than another biofilter without worms in domestic wastewater treatment. It can be applied into as pre-treatment for high concentration of COD and suspended solids of wastewater, which was in favor of the mitigation for substrate clogging and organic load in CWs (Xing et al., 2010).

Moreover, earthworms could help not only in enhancing the mass transfer process in the vertical direction through bioturbation but also in improving the food chain link with aquatic animals (Chiarawatchai and Nuengjamnong, 2009; Wu et al., 2013). Furthermore, the earthworm *Eisenia fetida* could promote the wetland plants growth due to the variation of nitrification potentials in rhizosphere (Xu et al., 2013). From this point of view, the application of earthworm in CWs is to the benefit of nutrients uptake and recycling values of plants. Similarly, *Tubifex tubifex* could remain alive at low temperatures and maintain high survival; their feces were also excellent manure and an adequate carbon source for denitrification. Its stimulations of bioturbation activity for microbial communities indirectly impacting the nitrogen cycle via mediated redox reactions and the usability of O_2. Kang et al. (2016) increased the TN and NO_3^--N removal efficiencies of wastewater by 22.92% and 40.87%, respectively, through the utilization of benthos in CWs. The use of animals was a good idea for better CW treatment performance at low temperatures through the synergistic effects among plant, microbe, and animal.

Table 1 Modifications were for enhancing CWs performance at low temperatures.

3.1.2. Plant configuration

The characteristics of plant configuration were mainly based on suitability for the local climatic environment, the size of the root system, the nutritional level of the water body, strong purification ability, anti-freeze characteristics, anti-fouling performance, and anti-impact load abilities (Allen et al., 2002). At present, according to the remarkable removal efficiencies of various plant species, the common plants applied in CWs included *Phragmites australis*, *Typha orientalis*, *Water hyacinth*, *Acorus calamus*, etc. (Brisson and Chazarenc, 2009; Chen et al., 2014). To deal with the influence of low temperature acting on CWs, a few plants have been cultivated for higher nutrient uptake. For instance, the evergreen *Lolium perenne* achieved 92.5% NH_4^+-N removal (0.2-2.6°C) based on its strong nitrogen absorption abilities (Ren et al., 2016). Due to its efficient intake of nitrogen and strong viability, *Carex aquatilis* screened in tundra wastewater treatment wetlands showed a 78% decrease in NH_3-N concentration at 0-5°C through its photosynthetically active radiation pattern (Yates et al., 2016).

Interestingly, the seasonal plant configuration was originally carried out on the basis of single plants applied to CWs. *Potamogeton crispus* enhanced the formation of cold-adapted ammonia-oxidizing bacteria by increasing the oxygen concentration in the wastewater and increasing oxygen transfer to plant roots (Fan et al., 2016); a seasonal plant collocation system (SPCS) consisting of *Potamogeton crispus* and *Phragmites australis* achieved plant growth and nutrient uptake sustainably during all seasons in northern China and achieved better removal NH_4^+-N and TP efficiencies (18.1% and 17.6%, respectively) than the group that only cultivated *P. australis* in winter. SPCSs were of prime strategic importance for the sustainable operation of CWs located in areas at low temperatures (Zhang et al., 2017).

3.1.3. Substrate supplements

The choice of the substrate in CWs was determined by factors such as mechanical strength, stability, specific surface area, porosity and surface roughness (Yang et al., 2018). To mitigate the adverse influences of low temperatures on wastewater treatment in CWs, scholars have used additional materials as supplementary enhancements of nitrogen removal. Cao and Zhang (2014) found that rice straw combined with an ecological floating bed could provide a favorable anaerobic environment and extra carbon sources for denitrification reactions and achieved removal efficiencies of 78.2% TN and 62.1% NO_3^--N in CWs (9.5-14.5°C) because a thick biofilm was formed by the decomposition of the supplemental material in eutrophic water bodies. Moreover, the natural rice straw was less expensive than nonbiodegradable materials. On the strength of the microscopic properties of the porous stem leaves of CW plants, Li et al. (2018)

prepared *Arundo donax*-derived biochar and filled it in substrate for reinforcing nitrogen adsorption. The 2 $mg\cdot g^{-1}d^{-1}$ release rate of the dissolved organic matter produced in the biochar helped increase the TN removal (85.62%) efficiency to approximately 50% higher than that in the no-biochar treatment in subsurface flow CWs (5.38±4.95°C). This botanical biochar with high porosity and a large surface area due to the porous structure of the hydrophyte provided numerous attachment sites and bioavailable carbon for denitrifying bacteria, which was beneficial to nitrogen transformation because of the anaerobic environment formed on the surface of the biochar. Moreover, compared with internal carbon sources, the appropriate dose of additional carbon sources was undetermined, and excessive doses would cause higher costs and adverse denitrification performance. Based on the concepts of plant management and resources recovery, the use of biochar was effective and necessary for enhancing CW performance at low temperatures; it also allowed the recycling of waste plant biomass resources and the prevention of secondary pollution of water bodies (Li et al., 2018).

In addition, Zhao et al. (2019) added iron-based material to a vertical subsurface-flow CW in order to enhance ion exchange and microbial reactions; this treatment achieved 65.62% TN removal efficiency in low carbon-nitrogen ratio wastewater (0-10°C). In terms of phosphorus removal, in addition to using conventional sand filter media, pine branches, activated sludge of active substances, iron slag and limestone were added to enhance the exchange between phosphorus and cations of Ca^{2+} and Fe^{3+}. However, this complementary effect was still needs the testing to determine whether it is suitable at low temperatures (Yang et al., 2018). Moreover, strengthening the degradation of microbes attached to substrates should also be considered for solving the problem of substrate desorption of phosphorus (Mietto et al., 2015).

3.2. Indirect modifications

3.2.1. Insulation and heat preservation

Various mulch materials, such as snow, straw, breathable film (polyvinyl chloride), carbonized reeds, and organic fillers, have been applied in horizontal subsurface flow CWs at low temperatures to maintain the temperature in a stable range or to prevent freezing to some extent through natural or artificial insulation (Akratos and Tsihrintzis, 2007). Materials covering the surface of CWs could reduce the energy lost due to wastewater evaporation, transportation and flow, and protect the CW internal microbe from the adverse effects of external low temperatures (Pang et al., 2015). Carbonized reed straw added to CWs maintained the CW wastewater temperature at 11-13°C (Yin and Shen, 1995). Similarly, Zhang et al. (2006) showed that adding a layer of plastic film on the surface of a CW maintained the wastewater temperature at range of 15-18°C, which greatly reducing the depth of frozen soil and increasing the mean removal rates of NH_4^+-N and COD by 38.2% and 17.6%, respectively. However, the introduction of the plastic film influenced the oxygen transfer rates, and the laying work was complicated although its cost was inexpensive. Moreover, the mulch film was breakable and difficult to maintain and would cause white pollution if not removed in time. The characteristics of coverings used for CW insulation should decompose substantially and without any secondary organic loading and have a neutral pH, high fiber content, balanced nutrient composition, good heat insulation and high moisture retention capacity (Wu et al., 2015). In addition, Wallace et al. (2003) found a naturally insulating air layer for heat preservation between the water surface and the ice surface at -4-18°C in Canada. Although ice cover did not cause secondary pollution problems in the same way as plant cover, it needed to be checked periodically. However, snow and ice cover are not reliable enough to insulate CWs during cold periods with finite snow accumulation. Moreover, when the ice surface melted in large areas because of temperature fluctuations, it was a complicated operation due to the frozen layer needs to be reformed. In addition to providing insulation and heat preservation, optimally designed greenhouse (to maintain the wastewater temperature above 8°C) for raising the temperature of bioecological horizontal subsurface flow CW systems achieved the annual mean removal rates of COD (85.01%), NH_3-N (70.98%) and TP (36.48%) (Gao and Hu, 2012). On the one hand, especially in winter, the greenhouse could be used for communication and entertainment towards the local people. On the other hand, it was also an ideal place for rice-cultivating in spring as well as brought in income for indigenous people. In terms of economic benefits, the greenhouse-structured wetlands have the great latent value for rural area in possession of the aquaculture industry (such as soft-shelled turtle greenhouse cultivation) (Hu et al., 2012; Wu et al., 2014).

3.2.2. Changes in operating conditions

The oxygen transfer rate was much higher in batch-type flow CWs (water supply and drainage at regular intervals for better oxygen capacity and continuously forming aerobic and anaerobic environments) than in conventional CWs at 12-25°C (Mesquita et al., 2017). Zhou et al. (2007) revealed that the NH_3-N and TN removal rates (5-10°C) by batch-type flow CWs reached 85.86% and 48.44%, respectively. Compared with the continuous flow CW, better COD removal efficiency, microbe respiration intensity, and hydrogenase activity were obtained. However, Zhang et al. (2012) believed that the higher DO level of the CW system inhibited the denitrification performance in the interior of the system although the batch-type operation mode did improve the denitrification ability and pollutant removal stability of the CWs at low temperatures. Moreover, batch-type flow CWs always restricted TN removal regardless of the HRT values.

Generally, a long HRT allows sufficient interaction between pollutants and wastewater. The HLR, which is important for microbial activity, organic matter degradation, and nutrient conversion, also affects the transport of pollutants and oxygen environment inside the CW (Põldvere et al., 2009; Rehman et al., 2017). Zhang et al. (2006) increased the removal rates (5-15°C) of NH_4^+-N and COD from 14% to 39% and 20% to 31%, respectively, after the hydraulic load was reduced from 30 cm/d to 15 cm/d. Conversely, the design of tower-hybrid CWs showed some nitrogen removal capacity at HLRs of 16 cm/d and 32 cm/d at mean temperatures close to 8°C (5.5°C at the lowest)

(Ye and Li, 2009). These different results may be because hydraulic efficiency varies between different CW configurations. In addition, Solano et al. (2004) reported that the highest organic removal rate was at a low HLR and a high HRT within a certain range (150, 75 mm/d and 1.5, 3.0 d, respectively), and the higher HRT (>3.5 d) contributed to an increase in organic matter removal (>70%) with a minimum mean temperature of 5°C and a maximum mean temperature of 15°C (Garfí et al., 2012).

3.2.3. Artificial aeration

Nitrification completion was closely related to the concentration of oxygen in CWs (Wu et al., 2014). However, in addition to direct reoxygenation from the atmosphere, the remaining amount of oxygen inside the CW was small since most of the oxygen derived from photosynthesis was used for the plant root respiration (Wang and Li, 2017). Artificial aeration could achieve 40-60% for TN removal efficiency by stimulating heterotrophic bacterial activity (Fan et al., 2013). Tao et al. (2010) found that eight hours of artificial aeration per day was enough to eliminate a large amount of NO_3^--N accumulation in continuous aerated subsurface flow CW effluent at 6.4±2.2°C. Continuous aeration significantly enhanced the conversion ratio of NH_4^+-N to NO_3^--N, but a continuous oxygen supply inhibited the subsequent denitrification due to the rapid expense of the carbon sources in the influent and the lack of an efficient hypoxia zone, while the denitrification process was responsible for more than half of the nitrogen removal (Maltais-Landry et al., 2007). The high operation costs of electromechanical devices for continuous aeration was also a potential problem, but the cost may be justified in mountainous regions where the space availability was limited (Foladori et al., 2013). However, the CW operation mode with intermittent aeration following step feeding effectively perfected the process of balancing denitrification with an effective nitrifying process; the additive carbon source supply in the new inflow and the alternation between aerobic and anaerobic environments achieved NH_4^+-N and TN removal efficiencies of 96% and 82%, respectively, at 14.7°C (Fan et al., 2013). The effect of step feeding on NO_3^--N accumulation was perhaps more prominent in continuously aerated CWs, but it should be weighed against the higher energy costs.

4. Future directions for the application of constructed wetlands at low temperatures

The aforementioned modifications for enhancing CW performance at low temperatures did make progress through the optimization of operations and spatial configuration in the CW interior and of the energy input and structural insulation in the CW exterior. With the goals of optimizing the CW components, perfecting the integrity of CW ecosystems and addressing emerging persistent organic pollutants (POPs), several future directions for CW application at low temperatures, such as the breeding of cold-resistant plants, bio-manipulation, and CWs integrated or combined with other treatments, were proposed for sustainable and diverse pollutants removal.

4.1. Breeding cold-resistant plants

Using CW plants that were adapted to the low-temperature environments would help sustain the absorption of wastewater nutrients in all seasons (Fan et al., 2016). In terms of the potential economic and technological effects, strengthening the breeding and cultivation of very cold-resistant plants was a popular trend (Kumar Meena et al., 2015). The generation of cold-resistant plants occurred mainly through the three pathways discussed below by changing the expression of the enzyme system or the hormone regulatory system and through gene mutation, respectively (Van Doom et al., 2013).

(1) Cold acclimation, i.e., appropriate low-temperature treatment of germinated seeds or seedlings by artificial or natural methods. Zhang et al. (2016) induced Mg-protoporphyrin IX (Mg-Proto IX) accumulation in Arabidopsis by use of the glutamate and $MgCl_2$ and found that Mg-Proto IX enhanced non-enzymatic antioxidants by activating antioxidant enzymes to maintain redox balance under cold stress. This processing mode could increase intracellular antioxidant enzyme activity and endogenous antioxidant levels (Calvo-Polanco et al., 2016; Dorffling et al., 1997), which alleviated the lipid peroxidation of membrane proteins and membranes caused by low temperature stress (Raju et al., 2018). (2) Chemical mutagenesis, i.e., exogenous ABA treatment increased the cold resistance of plants at normal temperatures while also inducing the expression of a variety of cold-stress genes to produce corresponding proteins (Huang et al., 2017). This was the process that increases the expression of

glycoproteins related to cell signal recognition at low temperatures and actuated the accumulation of a few cold-resistant substances that protect the biofilm in cells, such as proline, abscisic acid, and soluble sugars (Koehler et al., 2012). Moreover, Duan et al. (2019) revealed that the biosynthesis of flavonoids and phenylpropanoids was enriched in *Lycopersicon esculentum* Mill. under cold stress through analysis of the Kyoto Encyclopedia of Genes and Genomes pathways. (3) Radiation breeding induced plant mutations by X-rays, gamma-rays, ultraviolet rays, etc. to obtain new varieties. Radiation frequently generates point mutations that could effectively improve a single trait while maintaining the other excellent characteristics of a plant. The breeding procedure was also a relative short cycle and overcomes incompatibilities from distant hybridization (Ha et al., 2014).

These measures were used in the agricultural field to increase the yield of crops or to mitigate the adverse effects of climatic factors. Whether these pathways could generate functional genes or induce protein synthesis in cold-resistant plants effectively for pollutants uptake from wastewater of CW at low temperatures, it needs to be explored in future researches (Stamm et al., 2011; Zhang et al., 2014).

4.2. Perfecting the ecosystem of constructed wetland

The ecosystems of natural wetlands were more complex and stable than CW ecosystems (Liu et al., 2017). The more improved a CW ecosystem was, the more stable the purification effect would be. Based on the reinforced synergy mechanism of the seasonal application of CW organisms, an "(anti-pollution and cold-resistant) plant-benthos-microbe" synergistic enhancement CW was established.

First, the allocation of space for seasonal plantings (such as *Phragmites australis* and *Potamogeton crispus*) could help plants take in pollutants sustainably for growth in all seasons and increase the NH_4^+-N (18.1%) and TP (17.6%) removal efficiencies compared with those in CWs planted in one species. Plant roots not only supply oxygen and attachment points for microbes but also provide oxygen, food, and habitat for benthos (Zhang et al., 2017). Second, the addition of benthos (such as freshwater mussels, *Tubifex tubifex*, *Viviparidae* and *Chironomidae* larvae) could provide carbon dioxide and carbon from their feces for plant photosynthesis and microbial denitrification, respectively. Meanwhile, with the function of cold-resistant benthos, the process of ingestion and transformation of pollutants would further promote the TN and NO_3^--N removal efficiencies by 22.92% and 40.87%, respectively (Kang et al., 2016). Last, as the main component for wastewater purification in CWs, microbe activity was activated due to the preferable DO environment created by seasonal plant collocation and bioturbation by cold-resistant benthos. Moreover, the anaerobic environment provided by the enteric canals of benthic organisms was also beneficial to denitrification. This "organism loop" CW structure (**Fig. 4**) could be applied to the typical wetland situation at low temperatures in winter in northern China (Fan et al., 2016; Kang et al., 2016; Zhang et al., 2017).

The next studies for exploring the "organism loop" system at low temperatures in order to obtain more stable and sustainable pollutant removal efficiency should be related to the synergy between different cold-resistant plants in CWs. Moreover, the potential utility of benthonic animals such as *Tubifex tubifex* and freshwater mussels should be further tested for the stimulation dynamics of microbial processes, which benefited nitrogen transformation towards denitrification in CWs at low temperatures. In addition to the optimization of CWs for plants and animals, from the aspect of long-term stable pollutant removal efficiency, the function of the microbial population structure adapted to a low-temperature environment derived from a microbial inoculant needs to be screened further according to the metabolic characteristics and growing conditions of the microbes (Xu et al., 2017). For example, previous studies indicated that bio-augmentation, e.g., plant growth promoting rhizobacteria (PGPR), promoted the phosphorus uptake of plant since its secretion (such as extracellular phosphatase or organic acids) could convert the insoluble phosphate in soil into dissolving phosphorus that could be absorbed by plant. From this point of view, not only could it alleviate the clogging of phosphorus adsorption on surface of substrate, but also manifest the advantages of economic value in resources recovery of CW plant (Rehman et al., 2018).

It was useful for CWs containing high phosphorus concentration wastewater in combination with a greenhouse structure at low temperatures (Etesami and Maheshwari, 2018).

Fig. 4 "Plant-benthos-microbe" synergistic enhancement type CW.

4.3. Combination or integration with constructed wetlands

In addition to general pollutant removal by CWs, recently several treatment processes involving the degradation and transformation of specific pollutants by CWs in combination or integrated with systems such as algae ponds, photocatalytic oxidation processes, and metal redox processes have aroused broad attention. These combinations may improve the comprehensive treatment of pollutants in CWs compared to the application of a single technology.

4.3.1. Combination with algae ponds or photocatalytic oxidation

CWs in combination with stabilization ponds could improve secondary wastewater treatment, especially of dispersed rural wastewater or of concentrated wastewater in littoral zones at low temperatures (Šereš et al., 2017). In areas with many eco-ditches and channels, it was preferable to lower construction costs (Ham et al., 2004). Likewise, Zhao et al. (2016) significantly enhanced the TN removal of a CW combined with a high-rate algal pond through the oxygen enrichment of algae photosynthesis under 0-10°C. Meanwhile, the algae residue in CW may be used as carbon source by microbes in low carbon-nitrogen ratio wastewater. Aquaponics and greenhouse structures could also be applied to CWs (Lin et al., 2003). The ecological CW pond closely combined wastewater treatment with the comprehensive utilization of resources, which provided the economic benefits for local freshwater aquaculture and organic agriculture industries

(Hu et al., 2012; Wu et al., 2014).

Photoelectrons and photogenerated holes generated by irradiation react with oxygen and oxides of wastewater in different positions of TiO_2, translating them into ·OH and $\cdot O_2^-$ with strong oxidizing abilities (Antoniadis et al., 2007). The technology of TiO_2 photocatalysis for the degradation of several specific pollutants in wastewater has been shown in recent studies (Arana et al., 2008; Herrera-Melian et al., 2012; Wu et al., 2016). Interestingly, in combination with CWs, this system had a strong tolerance of peak hydraulic loads and achieved COD and total organic carbon removal efficiencies of 98.6% and 90%, respectively. The combination with CWs eliminated the deficiencies of the TiO_2-photocatalysis process alone. Arana et al. (2008) achieved an 84% phenol degradation rate with TiO_2-photocatalysis, but the concentration of the hydroquinone produced as an intermediate product was more poisonous than the phenol. The concentrations of both substances were decreased to satisfy the discharge standard through the additional effect of the CW. Likewise, solar TiO_2-photocatalysis degraded the 4-nitrophenol with sunlight during the day and the CW, as a pretreatment, further treated the effluent at night; this treatment mode was deemed to be remarkably flexible and efficient (Herrera-Melian et al., 2012).

It was worth mentioning that Palmqvist et al. (2015) demonstrated the feasibility of nanomaterials in natural purification systems by growing a fungal population in the rhizosphere of rapeseed and protecting the root from fungal infection using nano-TiO_2 particles. To utilize the strong photoreactivity of nano-TiO_2 (Legrini et al., 1993; Luan et al., 2014), the nanocatalyst particles were loaded onto the surface of the nanofiller with a structure designed to induce micropollutants to form a catalytic active center through modification (Luan et al., 2014). With the pollutants adsorbed to the surface of the carrier, the photocatalytic oxidation technology was applied to industrial wastewater (Abdelbasir and Shalan, 2019). This nanomaterials-photocatalysis in situ treatment system could adsorb more pollutants due to its specific surface area. Moreover, the drawbacks of CW treatment of high-strength wastewater and bio-refractory compounds such as POPs could be offset (Kundu and Mondal, 2019).

4.3.2. Integration with metal redox

Biogenic manganese (Mn) oxides with strong oxidizing properties and catalytic reactivity enhanced the removal of the emerging organic pollutant triclosan (TCS) and of common pollutants due to the recycling between the different valence states of Mn in anoxic and aerobic zones of CWs (Xie et al., 2018). In the anoxic zone, pollutants including TCS, NH_4^+-N, and organic carbon compounds were absorbed and then oxidized by Mn oxides (birnessite). In this process, Mn^{4+} converts to Mn^{2+}, and NO_3^--N was removed by denitrification coupled with Mn^{2+} oxidation. Subsequently, in the aerobic zone, the accumulated Mn-oxidizing bacteria reoxidize Mn^{2+} and produced biogenic Mn oxides with high specific surface area for the removal of low molecular products derived from the anoxic zone. Based on the circulation of the Mn valence state (**Fig. 5**), the removal efficiencies of TCS and NH_4^+-N in CW could be increased by

21.6% and 33.7% at a depth of 30 cm compared with those in a non-Mn CW. This use of metal redox is a good idea with the potential to address typical emerging organic pollutants and reduce the cost of substrates in CWs at low temperatures (Xie et al., 2018).

Fig. 5 The mechanism of CW integrated with Mn oxides for common and emerging organic pollutant removal.

In general, there was a great potential for the wetland plants in the effectiveness of wastewater treatment at high latitudes as the improvement and development of this technology (Raju et al., 2018). The additional plant and benthos would consume the huge manpower and material resources, and their investment was a considered factor (Liu et al., 2017). In terms of the engineering applications and the recycling of this system (Luan et al., 2013), the problems of the ecological safety of nanoparticles and the cost of nanomaterials were still need to be further addressed (Tahir et al., 2019). From a security perspective, the concentration of residual Mn in wastewater must be monitored constantly (Xie et al., 2018).

5. Conclusions

To address the bottleneck of wastewater treatment in CWs at low temperatures, countermeasures enhancing operational performance through direct or indirect modifications have been carried out and have increased pollutant removal efficiency to a certain degree. Based on the analysis of pollutant removal mechanisms and pathways in CWs at low temperatures, in the long term, future directions for enhancing CW treatment efficiency and sustainable operation could focus on several aspects, including mutation breeding for obtaining cold-resistant plants, bio-manipulation for perfecting CW ecosystems, and the combination or integration of CWs with technologies such as algae ponds, photocatalytic oxidation, and metal redox.

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Appendix A. Supplementary data

E-supplementary data for this work can be found in e-version of this paper online.

References

[1] Abdelbasir, S.M., Shalan, A.E., 2019. An overview of nanomaterials for industrial wastewater

treatment. Korean J. Chem. Eng. 36 (8), 1209-1225.

[2] Akratos, C.S., Tsihrintzis, V.A., 2007. Effect of temperature, HRT, vegetation and porous media on removal efficiency of pilot-scale horizontal subsurface flow constructed wetlands. Ecol. Eng. 29 (2), 173-191.

[3] Allen, W.C., Hook, P.B., Biederman, J.A., Stein, O.R., 2002. Temperature and wetland plant species effects on wastewater treatment and root zone oxidation. J. Environ. Qual. 31 (3), 1010-1016.

[4] An, S., Finlayson, C.M., 2018. Preface: wetland research in China. Mar. Freshwater Res. 69(5SI), I-III.

[5] Antoniadis, A., Takavakoglou, V., Zalidis, G., Poulios, I., 2007. Development and evaluation of an alternative method for municipal wastewater treatment using homogeneous photocatalysis and constructed wetlands. Catal. Today. 124 (3-4), 260-265.

[6] Arana, J., Cabo, C.G.I., Rodriguez, C.F., Melian, J.A.H., Mendez, J.A.O., Rodriguez, J.M.D., Pena, J.P., 2008. Combining TiO2-photocatalysis and wetland reactors for the efficient treatment of pesticides. Chemosphere. 71 (4), 788-794.

[7] Arden, S., Ma, X., 2018. Constructed wetlands for greywater recycle and reuse: A review. Sci. Total Environ. 630, 587-599.

[8] Bai, Y., Liang, J., Liu, R., Hu, C., Qu, J., 2014. Metagenomic analysis reveals microbial diversity and function in the rhizosphere soil of a constructed wetland. Environ. Technol. 35 (20), 2521-2527.

[9] Ben, Y., Chen, Z., Xu, Z., Jiang, A., 2009. Application of immobilized psychrotrophs in ICCBR to treat domestic wastewater and its microbiological investigation. Chin. Sci. Bull. 54 (9), 1599-1606.

[10] Blanco, I., Molle, P., Saenz De Miera, L.E., Ansola, G., 2016. Basic Oxygen Furnace steel slag

aggregates for phosphorus treatment. Evaluation of its potential use as a substrate in constructed wetlands. Water Res. 89, 355-365.

[11] Březinová, T., Vymazal, J., 2015. Seasonal growth pattern of *Phalaris arundinacea* in constructed wetlands with horizontal subsurface flow. Ecol. Eng. 80, 62-68.

[12] Brisson, J., Chazarenc, F., 2009. Maximizing pollutant removal in constructed wetlands: Should we pay more attention to macrophyte species selection? Sci. Total Environ. 407 (13), 3923-3930.

[13] Calvo-Polanco, M., Sánchez-Romera, B., Aroca, R., Asins, M.J., Declerck, S., Dodd, I.C., Martínez-Andújar, C., Albacete, A., Ruiz-Lozano, J.M., 2016. Exploring the use of recombinant inbred lines in combination with beneficial microbial inoculants (AM fungus and PGPR) to improve drought stress tolerance in tomato. Environ. Exp. Bot. 131, 47-57.

[14] Cao, W., Zhang, Y., 2014. Removal of nitrogen (N) from hypereutrophic waters by ecological floating beds (EFBs) with various substrates. Ecol. Eng. 62, 148-152.

[15] Chen, Y., Wu, X., Hao, J., Chen, M., Zhu, G., 2014. Selection and Purification Potential Evaluation of Woody Plant in Vertical Flow Constructed Wetlands in the Subtropical Area. Huanjing Kexue. 35 (2), 585-591.

[13] Chiarawatchai, N., Nuengjamnong, C., 2009. The Use of Earthworms in Lab-scale Constructed Wetlands to Treat Swine Wastewater. Thai J. Vet. Med. 39 (2), 157-162.

[14] Chong, S., Sen, T.K., Kayaalp, A., Ang, H.M., 2012. The performance enhancements of upflow anaerobic sludge blanket (UASB) reactors for domestic sludge treatment-A State-of-the-art review. Water Res. 46 (11), 3434-3470.

[15] Coban, O., Kuschk, P., Kappelmeyer, U., Spott, O., Martienssen, M., Jetten, M.S.M., Knoeller, K.,

2015. Nitrogen transforming community in a horizontal subsurface-flow constructed wetland. Water Res. 74, 203-212.

[15] Davidson, N.C., 2014. How much wetland has the world lost? Long-term and recent trends in global wetland area. Mar. Freshwater Res. 65 (10), 934-941.

[16] Davidson, N.C., Finlayson, C.M., 2018. Extent, regional distribution and changes in area of different classes of wetland. Mar. Freshwater Res. 69 (10), 1525-1533.

[17] Davidson, N.C., Fluet-Chouinard, E., Finlayson, C.M., 2018. Global extent and distribution of wetlands: trends and issues. Mar. Freshwater Res. 69 (4), 620-627.

[18]Davidson, N.C., van Dam, A.A., Finlayson, C.M., McInnes, R.J., 2019. Worth of wetlands: revised global monetary values of coastal and inland wetland ecosystem services. Mar. Freshwater Res. 70 (8), 1189-1194.

[19] Dixon, M.J.R., Loh, J., Davidson, N.C., Beltrame, C., Freeman, R., Walpole, M., 2016. Tracking global change in ecosystem area: The Wetland Extent Trends index. Biol. Conserv. 193, 27-35.

[20] Dorffling, K., Dorffling, H., Lesselich, G., Luck, E., Zimmermann, C., Melz, G., Jurgens, H.U., 1997. Heritable improvement of frost tolerance in winter wheat by in vitro selection of hydroxyproline-resistant proline overproducing mutants. Euphytica. 93 (1), 1-10.

[21] Du, L., Xuantung, T., Chen, Q., Wang, C., Wang, H., Xia, X., Zhou, Q., Xu, D., Wu, Z., 2018. Enhancement of microbial nitrogen removal pathway by vegetation in Integrated Vertical-Flow Constructed Wetlands (IVCWs) for treating reclaimed water. Bioresour. Technol. 249, 644-651.

[22] Duan, X.F., Chen, X.H., Wang, S., Zhang, X.C., 2019. Transcriptome Sequencing and Analysis of Chilling Tolerance Mutant Tomato under Low Temperature. Russ. J. Plant Physl. 66 (1), 110-118.

[23] Duan, Y. X., Shi, Y., Shao, X. L., Zeng, M., Lv, J. H., Xu, D. Y., Lu, X. Q., (2016). Stable operation technology of constructed wetland under double stress of high salt and low temperature. Urban Urban Environ. Urban Ecol. (03), 37-41.

[24] Etesami, H., Maheshwari, D.K., 2018. Use of plant growth promoting rhizobacteria (PGPRs) with multiple plant growth promoting traits in stress agriculture: Action mechanisms and future prospects. Ecotox. Environ. Safe. 156, 225-246.

[25] Fan, J., Liang, S., Zhang, B., Zhang, J., 2013. Enhanced organics and nitrogen removal in batch-operated vertical flow constructed wetlands by combination of intermittent aeration and step feeding strategy. Environ. Sci. Pollut. R. 20 (4), 2448-2455.

[26] Fan, J., Zhang, J., Ngo, H.H., Guo, W., Yin, X., 2016. Improving low-temperature performance of surface flow constructed wetlands using *Potamogeton crispus* L. plant. Bioresour. Technol. 218, 1257-1260.

[27] Faulwetter, J.L., Gagnon, V., Sundberg, C., Chazarenc, F., Burr, M.D., Brisson, J., Camper, A.K., Stein, O.R., 2009. Microbial processes influencing performance of treatment wetlands: A review. Ecol. Eng. 35 (6), 987-1004.

[28] Feng, X., Yang, Y., Zheng, Z., Tang, X., Zhang, X., Dai, Y., Xiong, C., 2019. Application of a recycled standing combined constructed wetland system for the treatment of heavy metals from mixed wastewater in a rural area. J. Agro-Environ. Sci. 38, 671-679.

[29] Foladori, P., Ruaben, J., Ortigara, A.R.C., 2013. Recirculation or artificial aeration in vertical flow constructed wetlands: A comparative study for treating high load wastewater. Bioresour. Technol. 149, 398-405.

[30] Gao, D., Hu, Q., 2012. Bio-contact oxidation and greenhouse-structured wetland system for rural sewage recycling in cold regions: A full-scale study. Ecol. Eng. 49, 249-253.

[31] Garfí, M., Pedescoll, A., Bécares, E., Hijosa-Valsero, M., Sidrach-Cardona, R., García, J., 2012. Effect of climatic conditions, season and wastewater quality on contaminant removal efficiency of two experimental constructed wetlands in different regions of Spain. Sci. Total Environ. 437, 61-67.

[32] Gong, P., Niu, Z., Cheng, X., Zhao, K., Zhou, D., Guo, J., Liang, L., Wang, X., Li, D., Huang, H., Wang, Y., Wang, K., Li, W., Wang, X., Ying, Q., Yang, Z., Ye, Y., Li, Z., Zhuang, D., Chi, Y., Zhou, H., Yan, J., 2010. China's wetland change (1990-2000) determined by remote sensing. Sci. China Earth Sci. 53 (7), 1036-1042.

[33] Gorgoglione, A., Torretta, V., 2018. Sustainable Management and Successful Application of Constructed Wetlands: A Critical Review. Sustainability. 10 (391011).

[34] Ha, B., Lee, K.J., Velusamy, V., Kim, J., Kim, S.H., Ahn, J., Kang, S., Kim, D.S., 2014. Improvement of soybean through radiation-induced mutation breeding techniques in Korea. Plant Genet. Resour. C. 121 (SI), S54-S57.

[35] Ham, J.H., Yoon, C.G., Hwang, S.J., Jung, K.W., 2004. Seasonal performance of constructed wetland and winter storage pond for sewage treatment in Korea. J. Environ. Sci. Heal. A. 39 (5), 1329-1343.

[36] Harada, J., Inoue, T., Kato, K., Uraie, N., Sakuragi, H., 2015. Performance evaluation of hybrid treatment wetland for six years of operation in cold climate. Environ. Sci. Pollut. R. 22 (17), 12861-12869.

[37] Herrera-Melian, J.A., Martin-Rodriguez, A.J., Ortega-Mendez, A., Arana, J., Dona-Rodriguez, J.M.,

Perez-Pena, J., 2012. Degradation and detoxification of 4-nitrophenol by advanced oxidation technologies and bench-scale constructed wetlands. J. Environ. Manage. 105, 53-60.

[38] Hu, Z., Lee, J.W., Chandran, K., Kim, S., Khanal, S.K., 2012. Nitrous Oxide (N2O) Emission from Aquaculture: A Review. Environ. Sci. Technol. 46 (12), 6470-6480.

[39] Huang, J., Cai, W., Zhong, Q., Wang, S., 2013. Influence of temperature on micro-environment, plant eco-physiology and nitrogen removal effect in subsurface flow constructed wetland. Ecol. Eng. 60, 242-248.

[40] Huang, W., Zhao, Y., Wu, J., Zhang, J., Zheng, Z., 2014. Effects of different influent C/N ratios on the performance of various earthworm eco-filter systems: nutrient removal and greenhouse gas emission. World J. Microb. Biot. 30 (1), 109-118.

[41] Huang, X., Shi, H., Hu, Z., Liu, A., Amombo, E., Chen, L., Fu, J., 2017. ABA Is Involved in Regulation of Cold Stress Response in Bermudagrass. Front. Plant Sci. 8 (1613).

[42] Hwang, J.H., Oleszkiewicz, J.A., 2007. Effect of cold-temperature shock on nitrifiication. Water Environ. Res. 79 (9), 964-968.

[43] Isaka, K., Kimura, Y., Osaka, T., Tsuneda, S., 2012. High-rate denitrification using polyethylene glycol gel carriers entrapping heterotrophic denitrifying bacteria. Water Res. 46 (16), 4941-4948.

[44] Janse, J.H., van Dam, A.A., Hes, E.M.A., de Klein, J.J.M., Finlayson, C.M., Janssen, A.B.G., van Wijk, D., Mooij, W.M., Verhoeven, J.T.A., 2019. Towards a global model for wetlands ecosystem services. Curr. Opin. Env. Sust. 36 (SI), 11-19.

[45] Jenssen, P.D., Maehlum, T., Krogstad, T., 1993. Potential use of constructed wetlands for waste-water treatment in northern environments. Water Sci. Technol. 28 (10), 149-157.

[46] Junk, W.J., An, S., Finlayson, C.M., Gopal, B., Kvet, J., Mitchell, S.A., Mitsch, W.J., Robarts, R.D., 2013. Current state of knowledge regarding the world's wetlands and their future under global climate change: a synthesis. Aquat. Sci. 75 (1), 151-167.

[47] Jurado, G.B., Callanan, M., Gioria, M., Baars, J.R., Harrington, R., Kelly-Quinn, M., 2009. Comparison of macroinvertebrate community structure and driving environmental factors in natural and wastewater treatment ponds. Hydrobiologia. 634 (1), 153-165.

[48] Kang, W., Chai, H., Xiang, Y., Chen, W., Shao, Z., He, Q., 2017. Assessment of low concentration wastewater treatment operations with dewatered alum sludge-based sequencing batch constructed wetland system. Sci. Rep. 7(1).

[49] Kang, Y., Zhang, J., Xie, H., Guo, Z., Li, P., Cheng, C., Lv, L., 2016. Enhancement of the performance of constructed wetlands for wastewater treatment in winter: the effect of Tubifex tubifex. RSC Adv. 6 (41), 34841-34848.

[50] Kivaisi, A.K., 2001. The potential for constructed wetlands for wastewater treatment and reuse in developing countries: a review. Ecol. Eng. 16 (4), 545-560.

[51] Koehler, G., Wilson, R.C., Goodpaster, J.V., Sonsteby, A., Lai, X., Witzmann, F.A., You, J., Rohloff, J., Randall, S.K., Alsheikh, M., 2012. Proteomic Study of Low-Temperature Responses in Strawberry Cultivars (Fragaria x ananassa) That Differ in Cold Tolerance. Plant Physiol. 159 (4), 1787-1805.

[52] Kumar Meena, R., Kumar Singh, R., Pal Singh, N., Kumari Meena, S., Singh Meena, V., 2015. Isolation of low temperature surviving plant growth−promoting rhizobacteria (PGPR) from pea (*Pisum sativum* L.) and documentation of their plant growth promoting traits. Biocatal. Agric.

Biotechnol. 4 (4), 806-811.

[53] Kumar, S., Dutta, V., 2019. Constructed wetland microcosms as sustainable technology for domestic wastewater treatment: an overview. Environ. Sci. Pollut. R. 26 (12SI), 11662-11673.

[54] Kundu, A., Mondal, A., 2019. In-situ synthesis of self Ti3+ doped TiO2/RGO nanocomposites as efficient photocatalyst to remove organic dyes from wastewater under direct sunlight irradiation. Mater. Res. Express. 6 (8).

[55] Legrini, O., Oliveros, E., Braun, A.M., 1993. Photochemical processes for water-treatment. Chem. Rev. 93 (2), 671-698.

[56] Li, H.Z., Wang, S., Ye, J.F., Xu, Z.X., Jin, W., 2011. A practical method for the restoration of clogged rural vertical subsurface flow constructed wetlands for domestic wastewater treatment using earthworm. Water Sci. Technol. 63 (2), 283-290.

[57] Li, J., Fan, J., Zhang, J., Hu, Z., Liang, S., 2018. Preparation and evaluation of wetland plant-based biochar for nitrogen removal enhancement in surface flow constructed wetlands. Environ. Sci. Pollut. R. 25 (14), 13929-13937.

[58] Lin, J.L., Kuo, W.C., Chang, Y.M., Surampalli, R.Y., Kao, C.M., 2015. Development of a Natural Treatment System for Stream Water Purification: Mechanisms and Environmental Impacts Evaluation. J. Environ. Eng. 141 (11).

[59] Lin, Y.F., Jing, S.R., Lee, D.Y., 2003. The potential use of constructed wetlands in a recirculating aquaculture system for shrimp culture. Environ. Pollut. 123 (1), 107-113.

[60] Liu, Z., Xie, H., Hu, Z., Zhang, J., Zhang, J., Sun, H., Lan, W., 2017. Role of Ammonia-Oxidizing Archaea in Ammonia Removal of Wetland Under Low-Temperature Condition. Water, Air, Soil

Pollut. 228 (9).

[61] Luan, Y., Feng, Y., Cui, H., Cao, Y., Jing, L., 2014. Enhanced Photocatalytic Activity of P25 TiO2 after Modification with Phosphate-Treated Porous SiO2. ChemPlusChem. 79 (9), 1271-1277.

[62] Luan, Y., Feng, Y., Wang, W., Xie, M., Jing, L., 2013. Synthesis of BiOBr-TiO2 Nanocrystalline Composite by Microemulsion-Like Chemical Precipitation Method and Its Photocatalytic Activity. Acta Phys. Chim. Sin. 29 (12), 2655-2660.

[63] Maltais-Landry, G., Chazarenc, F., Comeau, Y., Troesch, S., Brisson, J., 2007. Effects of artificial aeration, macrophyte species, and loading rate on removal efficiency in constructed wetland mesocosms treating fish farm wastewater. J. Environ. Eng. Sci. 6 (4), 409-414.

[64] McCarey, A., Anderson, B.C., Martin, D., 2004. Monitoring spatial and temporal variations of phosphorus within a cold climate subsurface flow constructed wetland. J. Environ. Eng. Sci. 3 (1), 51-60.

[65] Mesquita, M.C., Albuquerque, A., Amaral, L., Nogueira, R., 2017. Seasonal variation of nutrient removal in a full-scale horizontal constructed wetland. Energy Procedia. 136, 225-232.

[66] Mietto, A., Politeo, M., Breschigliaro, S., Borin, M., 2015. Temperature influence on nitrogen removal in a hybrid constructed wetland system in Northern Italy. Ecol. Eng. 75, 291-302.

[67] Moomaw, W.R., Chmura, G.L., Davies, G.T., Finlayson, C.M., Middleton, B.A., Natali, S.M., Perry, J.E., Roulet, N., Sutton-Grier, A.E., 2018. Wetlands In a Changing Climate: Science, Policy and Management. Wetlands. 38 (2), 183-205.

[68] Palmqvist, N.G.M., Bejai, S., Meijer, J., Seisenbaeva, G.A., Kessler, V.G., 2015. Nano titania aided clustering and adhesion of beneficial bacteria to plant roots to enhance crop growth and stress

management. Sci. Rep. 5 (10146).

[69] Pang, C., Li, A., Qiu, S., Wang, L., Yang, J., Ma, F., Ren, N., 2015. A novel subsurface flow constructed wetland system used in anvanced wastewater treatment for nutrient removal in a cold area. Bulg. Chem. Commun. 47 (D), 173-178.

[70] Petersen, J.E., Brandt, E.C., Grossman, J.J., Allen, G.A., Benzing, D.H., 2015. A controlled experiment to assess relationships between plant diversity, ecosystem function and planting treatment over a nine year period in constructed freshwater wetlands. Ecol. Eng. 82, 531-541.

[71] Põldvere, E., Karabelnik, K., Noorvee, A., Maddison, M., Nurk, K., Zaytsev, I., Mander, Ü., 2009. Improving wastewater effluent filtration by changing flow regimes—Investigations in two cold climate pilot scale systems. Ecol. Eng. 35 (2), 193-203.

[72] Postila, H., Ronkanen, A., Kløve, B., 2015. Wintertime purification efficiency of constructed wetlands treating runoff from peat extraction in a cold climate. Ecol. Eng. 85, 13-25.

[73] Raju, S.K.K., Barnes, A.C., Schnable, J.C., Roston, R.L., 2018. Low-temperature tolerance in land plants: Are transcript and membrane responses conserved? Plant Sci. 276, 73-86.

[74] Rehman, K., Imran, A., Amin, I., Afzal, M., 2018. Inoculation with bacteria in floating treatment wetlands positively modulates the phytoremediation of oil field wastewater. J. Hazard. Mater., 349, 242-251.

[75] Rehman, F., Pervez, A., Mahmood, Q., Nawab, B., 2017. Wastewater remediation by optimum dissolve oxygen enhanced by macrophytes in constructed wetlands. Ecol. Eng. 102, 112-126.

[76] Ren, Y., Liu, Y., Sun, J., Lu, H., Yang, L., Chen, C., Han, Y., 2016a. *Lolium Perenne* as the Cultivation Plant in Hydroponic Ditch and Constructed Wetland to Improve Wastewater Treatment

Efficiency in a Cold Region. Wetlands. 36 (4), 659-665.

[77] Sani, A., Scholz, M., Bouillon, L., 2013. Seasonal assessment of experimental vertical-flow constructed wetlands treating domestic wastewater. Bioresour. Technol. 147, 585-596.

[78] Semeraro, T., Giannuzzi, C., Beccarisi, L., Aretano, R., De Marco, A., Pasimeni, M.R., Zurlini, G., Petrosillo, I., 2015. A constructed treatment wetland as an opportunity to enhance biodiversity and ecosystem services. Ecol. Eng. 82, 517-526.

[79] Šereš, M., Hnátková, T., Vymazal, J., Vaněk, T., 2017. Removal Efficiency of Constructed Wetland for Treatment of Agricultural Wastewaters. Chem. J. Mold. 12 (1), 45-52.

[80] Sinha, R.K., Bharambe, G., Chaudhari, U., 2008. Sewage treatment by vermifiltration with synchronous treatment of sludge by earthworms: a low-cost sustainable technology over conventional systems with potential for decentralization. Environmentalist, 28(4), 409-420.

[81] Solano, M.L., Soriano, P., Ciria, M.P., 2004. Constructed wetlands as a sustainable solution for wastewater treatment in small villages. Biosyst. Eng. 87 (1), 109-118.

[82] Song, Z.W., Zheng, Z.P., Li, J., Sun, X.F., Han, X.Y., Wang, W., Xu, M., 2006. Seasonal and annual performance of a full-scale constructed wetland system for sewage treatment in China. Ecol. Eng. 26 (3), 272-282.

[83] Stamm, P., Ramamoorthy, R., Kumar, P.P., 2011. Feeding the extra billions: strategies to improve crops and enhance future food security. Plant Biotechnol. Rep. 5 (2), 107-120.

[84] Stefanakis, A.I., Tsihrintzis, V.A., 2012. Effects of loading, resting period, temperature, porous media, vegetation and aeration on performance of pilot-scale vertical flow constructed wetlands. Chem. Eng. J. 181, 416-430.

[85] Stottmeister, U., Wießner, A., Kuschk, P., Kappelmeyer, U., Kästner, M., Bederski, O., Müller, R.A., Moormann, H., 2003. Effects of plants and microorganisms in constructed wetlands for wastewater treatment. Biotechnol. Adv. 22 (1-2), 93-117.

[86] Tahir, M.B., Ali, S., Rizwan, M., 2019. A review on remediation of harmful dyes through visible light-driven WO3 photocatalytic nanomaterials. Int. J. Environ. Sci. Te. 16 (8), 4975-4988.

[87] Tao, M., He, F., Xu, D., Li, M., Wu, Z., 2010. How Artificial Aeration Improved Sewage Treatment of an Integrated Vertical-Flow Constructed Wetland. Pol. J. Environ. Stud. 19 (1), 183-191.

[88] Taylor, C.R., Hook, P.B., Stein, O.R., Zabinksi, C.A., 2011. Seasonal effects of 19 plant species on COD removal in subsurface treatment wetland microcosms. Ecol. Eng. 37 (5SI), 703-710.

[89] Van de Moortel, A.M.K., Meers, E., De Pauw, N., Tack, F.M.G., 2010. Effects of Vegetation, Season and Temperature on the Removal of Pollutants in Experimental Floating Treatment Wetlands. Water, Air, Soil Pollut. 212 (1-4), 281-297.

[90] Van Doorn, W.G., Celikel, F.G., Pak, C., Harkema, H., 2013. Delay of Iris flower senescence by cytokinins and jasmonates. Physiol. Plantarum. 148 (1), 105-120.

[91] Wallace, S., G. Parkin., Cross, C., 2001. Cold climate wetlands: design and performance. Water Sci. Technol. 44 (11-12), 259-265.

[92] Wang, L., Li, T., 2017. Seasonal effects of pre-aeration on microbial processes for nitrogen removal in constructed wetlands. Environ. Sci. Pollut. R. 24 (4), 3810-3819.

[93] Wang, L., Zheng, Z., Luo, X., Zhang, J., 2011. Performance and mechanisms of a microbial-earthworm ecofilter for removing organic matter and nitrogen from synthetic domestic wastewater. J. Hazard. Mater. 195, 245-253.

[94] Wang, M., Zhang, D., Dong, J., Tan, S.K., 2018. Application of constructed wetlands for treating agricultural runoff and agro-industrial wastewater: a review. Hydrobiologia. 805 (1), 1-31.

[95] Wang, M., Zhang, D.Q., Dong, J.W., Tan, S.K., 2017. Constructed wetlands for wastewater treatment in cold climate −A review. J. Environ. Sci. 57, 293-311.

[96] Wood, S.L., Wheeler, E.F., Berghage, R.D., Graves, R.E., 1999. Temperature effects on wastewater nitrate removal in laboratory-scale constructed wetlands. Trans. ASAE. 42 (1), 185-190.

[97] Wu, B., Zhang, G., Zhang, S., 2016. Fate and implication of acetylacetone in photochemical processes for water treatment. Water Res. 101, 233-240.

[98] Wu, H., Zhang, J., Ngo, H.H., Guo, W., Hu, Z., Liang, S., Fan, J., Liu, H., 2015. A review on the sustainability of constructed wetlands for wastewater treatment: Design and operation. Bioresour. Technol. 175, 594-601.

[99] Wu, L., Li, X., Song, H., Wang, G., Jin, Q., Xu, X., Gao, Y., 2013. Enhanced removal of organic matter and nitrogen in a vertical-flow constructed wetland with *Eisenia foetida*. Desalin. Water Treat. 51 (40-42), 7460-7468.

[100] Wu, S., Kuschk, P., Brix, H., Vymazal, J., Dong, R., 2014. Development of constructed wetlands in performance intensifications for wastewater treatment: A nitrogen and organic matter targeted review. Water Res. 57, 40-55.

[101] Wu, S., Lyu, T., Zhao, Y., Vymazal, J., Arias, C.A., Brix, H., 2018. Rethinking Intensification of Constructed Wetlands as a Green Eco-Technology for Wastewater Treatment. Environ. Sci. Technol. 52 (4), 1693-1694.

[102] Wu, X., Wu, H., Ye, J., 2014. Purification effects of two eco-ditch systems on Chinese soft-shelled

turtle greenhouse culture wastewater pollution. Environ. Sci. Pollut. R. 21(8), 5610-5618.

[103] Xie, H., Yang, Y., Liu, J., Kang, Y., Zhang, J., Hu, Z., Liang, S., 2018. Enhanced triclosan and nutrient removal performance in vertical up-flow constructed wetlands with manganese oxides. Water Res. 143, 457-466.

[104] Xie, S.G., Zhang, X.J., Wang, Z.S., 2003. Temperature effect on aerobic denitrification and nitrification. J. Environ. Sci. 15 (5), 669-673.

[105] Xing, M., Li, X., Yang, J., 2010. Treatment performance of small-scale vermifilter for domestic wastewater and its relationship to earthworm growth, reproduction and enzymatic activity. Afr. J. Biotechnol. 9(44), 7513-7520.

[106] Xu, D., Li, Y., Howard, A., Guan, Y., 2013. Effect of earthworm Eisenia fetida and wetland plants on nitrification and denitrification potentials in vertical flow constructed wetland. Chemosphere, 92(2), 201-206.

[107] Xu, W., Fan, X., Ma, J., Pimm, S.L., Kong, L., Zeng, Y., Li, X., Xiao, Y., Zheng, H., Liu, J., Wu, B., An, L., Zhang, L., Wang, X., Ouyang, Z., 2019. Hidden Loss of Wetlands in China. Curr. Biol. 29 (18), 3065-3071.

[108] Xu, Y., He, T., Li, Z., Ye, Q., Chen, Y., Xie, E., Zhang, X., 2017. Nitrogen Removal Characteristics of *Pseudomonas putida* Y-9 Capable of Heterotrophic Nitrification and Aerobic Denitrification at Low Temperature. Biomed Res. Int. 2017, 7.

[109] Xu, Z., Ben, Y., Chen, Z., Jiang, A., Shen, J., Han, X., 2018. Application and microbial ecology of psychrotrophs in domestic wastewater treatment at low temperature. Chemosphere. 191, 946-953.

[110] Yang, Y., Zhao, Y., Liu, R., Morgan, D., 2018. Global development of various emerged substrates

utilized in constructed wetlands. Bioresour. Technol. 261, 441-452.

[111] Yates, C.N., Varickanickal, J., Cousins, S., Wootton, B., 2016. Testing the ability to enhance nitrogen removal at cold temperatures with *C. aquatilis* in a horizontal subsurface flow wetland system. Ecol. Eng. 94, 344-351.

[112] Ye, F., Li, Y., 2009. Enhancement of nitrogen removal in towery hybrid constructed wetland to treat domestic wastewater for small rural communities. Ecol. Eng. 35 (7), 1043-1050.

[113] Yeh, T.Y., Pan, C.T., Ke, T.Y., Kuo, T.W., 2010. Organic Matter and Nitrogen Removal within Field-Scale Constructed Wetlands: Reduction Performance and Microbial Identification Studies. Water Environ. Res. 82 (1), 27-33.

[114] Yin, H., Shen, W.R., 1995. Using reed beds for winter operation of wetland treatment system for wastewater. Water Sci. Technol. 32 (3), 111-117.

[115] Yu, X., Ding, S., Zou, Y., Xue, Z., Lyu, X., Wang, G., 2018. Review of Rapid Transformation of Floodplain Wetlands in Northeast China: Roles of Human Development and Global Environmental Change. Chinese Geogr. Sci. 28 (4), 654-664.

[116] Zhang, D.Q., Tan, S.K., Gersberg, R.M., Zhu, J., Sadreddini, S., Li, Y., 2012. Nutrient removal in tropical subsurface flow constructed wetlands under batch and continuous flow conditions. J. Environ. Manage. 96 (1), 1-6.

[117] Zhang, J., Shao, W. S., He, M., Hu, H. Y., Gao, B. Y., 2006. Treatment performance and enhancement of subsurface constructed wetland treating polluted river water in winter. Environ. Sci. 27 (8), 1560-1564.

[118] Zhang, J., Sun, H., Wang, W., Hu, Z., Yin, X., Ngo, H.H., Guo, W., Fan, J., 2017. Enhancement of

surface flow constructed wetlands performance at low temperature through seasonal plant collocation. Bioresour. Technol. 224, 222-228.

[119] Zhang, J., Wu, P., Hao, B., Yu, Z., 2011. Heterotrophic nitrification and aerobic denitrification by the bacterium *Pseudomonas stutzeri* YZN-001. Bioresour. Technol. 102 (21), 9866-9869.

[120] Zhang, X., Zhang, X., Li, H., Wang, L., Zhang, C., Xing, X., Bao, C., 2014. Atmospheric and room temperature plasma (ARTP) as a new powerful mutagenesis tool. Appl. Microbiol. Biot. 98 (12), 5387-5396.

[121] Zhang, Z., Wu, Z., Feng, L., Dong, L., Song, A., Yuan, M., Chen, Y., Zeng, J., Chen, G., Yuan, S., 2016. Mg-Protoporphyrin IX Signals Enhance Plant’ s Tolerance to Cold Stress. Front. Plant Sci. 7.

[122] Zhao, X., Yang, J., Bai, S., Ma, F., Wang, L., 2016. Microbial population dynamics in response to bioaugmentation in a constructed wetland system under 10°C. Bioresour. Technol. 205, 166-173.

[123] Zhao, Y., Yan, C., Li, Y., Li, J., Yang, M., Nie, E., Zheng, Z., Luo, X., 2012. Effect of C/N ratios on the performance of earthworm eco-filter for treatment of synthetics domestic sewage. Environ. Sci. Pollut. R. 19 (9), 4049-4059.

[124] Zhao, Y., Zhang, Y., Ge, Z., Hu, C., Zhang, H., 2014. Effects of influent C/N ratios on wastewater nutrient removal and simultaneous greenhouse gas emission from the combinations of vertical subsurface flow constructed wetlands and earthworm eco-filters for treating synthetic wastewater. Environ. Sci. Proc. Imp. 16 (3), 567-575.

[125] Zhao, Z., Song, X., Wang, Y., Wang, D., Wang, S., He, Y., Ding, Y., Wang, W., Yan, D., Wang, J., 2016. Effects of algal ponds on vertical flow constructed wetlands under different sewage application techniques. Ecol. Eng. 93, 120-128.

[126] Zhao, Z., Xu, C., Zhang, X., Song, X., 2019. Addition of iron materials for improving the removal efficiencies of multiple contaminants from wastewater with a low C/N ratio in constructed wetlands at low temperatures. Environ. Sci. Pollut. R. 26 (12), 1988-11997.

[127] Zheng, Y., Niu, Z., Gong, P., Wang, J., 2015. A database of global wetland validation samples for wetland mapping. Sci. Bull. 60 (4), 428-434.

[128] Zhou, J., Wang, J. X., Zhang, Q., Zhang, Z., Pan, F., 2007. Research on nitrogen removal efficiency in a sequential batch constructed wetland at low temperatures in winter. Acta Sci. Circumstantiae. 27 (10), 1652-1656.

[129] Zhou, J., Zhang, J. H., Chen, J., Li, M., 2014. Analysis of Spatial Structure onWetland Nature Reserves,Wetland Parks and International ImportantWetlands in China. Wetland Sci. 12 (05), 597-605.

[130] Zhou, X., Liang, C., Jia, L., Feng, L., Wang, R., Wu, H., 2018. An innovative biochar-amended substrate vertical flow constructed wetland for low C/N wastewater treatment: Impact of influent strengths. Bioresour. Technol. 247, 844-850.

[131] Zietzschmann, F., Mitchell, R.L., Jekel, M., 2015. Impacts of ozonation on the competition between organic micro-pollutants and effluent organic matter in powdered activated carbon adsorption. Water Res. 84, 153-160.

Figures caption

Fig. 1 The distribution of CWs in administrative regions of China (The site and size of circles indicates provincial capital and area respectively).

Fig. 2 Main pathways of pollutants removal in CWs. (1) OP: Organophosphorus; DP: Dissolved phosphorus; IP: Inorganic phosphorus; PP: Particulate phosphorus. (2) Account for the proportion of pollutants removal: ① 5.4-20.1% N, 4.8-22.3% P; ② 4.5-8.3% N, 36.2-49.7% P; ③ 89-96% N.

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Fig. 5 The mechanism of CW integrated with Mn oxides for common and emerging organic pollutant removal.

Table caption

Table 1 Modifications were for enhancing CWs performance at low temperatures. MI indicates microbial inoculant. WT means wastewater type including raw (R), town (T), domestic (D), synthetic (S), farm (F), municipal (M) wastewater. T is the temperature.

Supplementary file

Fig. S1 The area distribution of Ramsar sites around the world (Dixon et al., 2016; Davidson and Finlayson, 2018).

New insights for enhancing the performance of constructed wetlands at low temperatures

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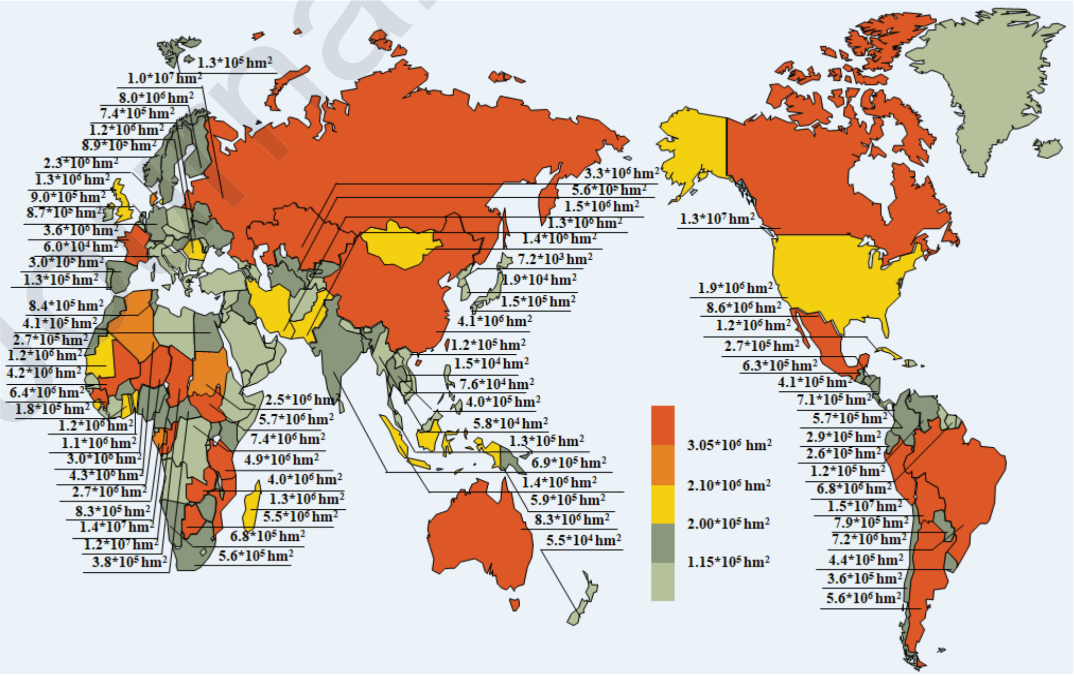

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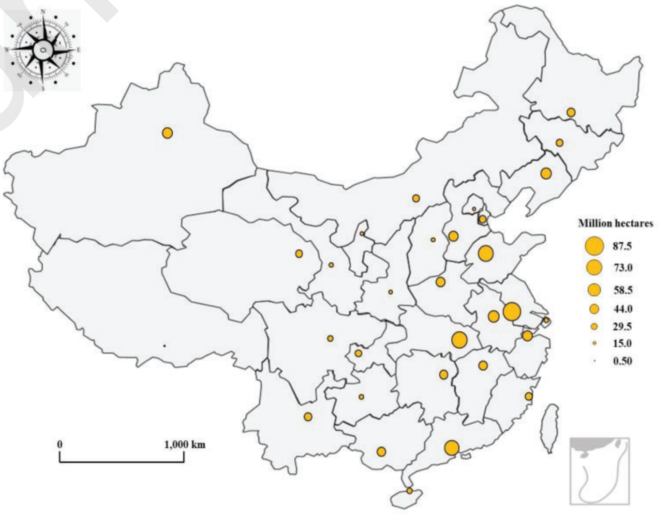

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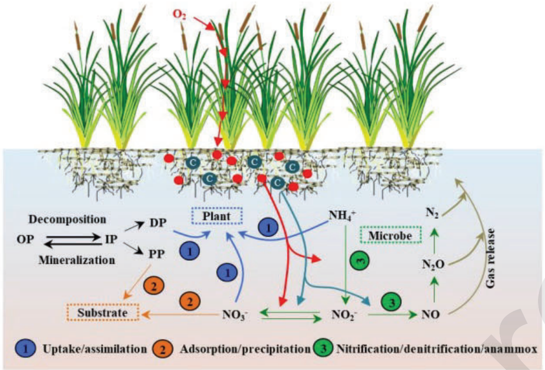

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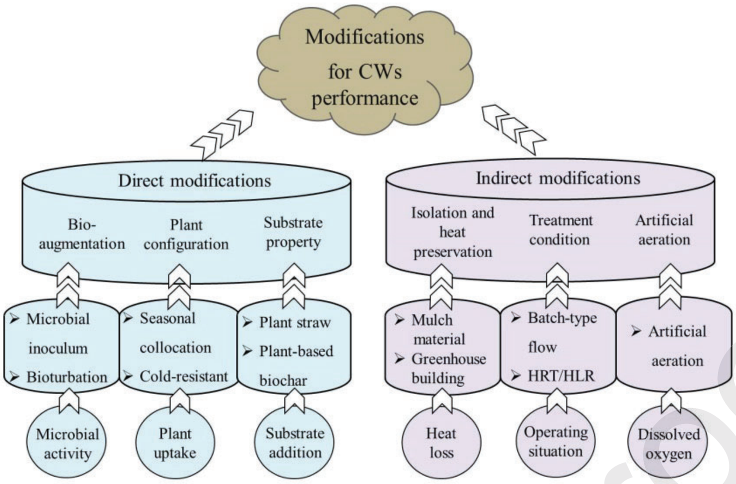

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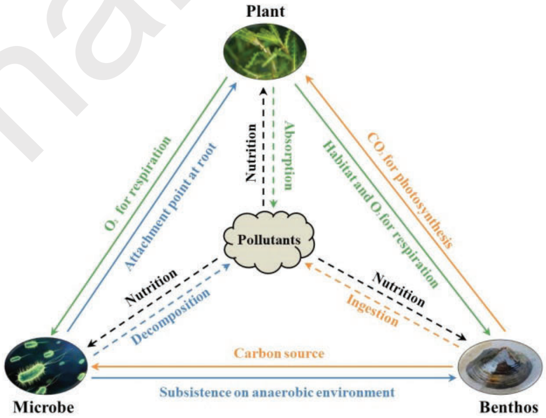

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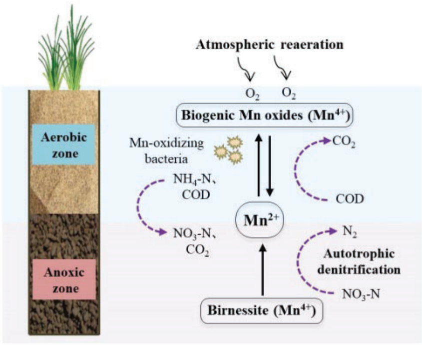

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Modification	Method	CW type	Scale	W	HRT	T (°C)	Removal efficiency (%)				Reference
							COD	NH_4^+-N	TN	TP	
Bio-aug–mentation	MI	VSSF	Lab	R	4 d	8-12	60	84.5	74.2	NA	(Zhao et al., 2016)
	MI	FSS	Pilot	T	3 d	5	30	35.4	33.6	28	(Duan et al., 2016)
	MI	HSSF	Lab	D	4 d	7-11	78.5	83.1	74.6	68	(Faulwetter et al., 2009)

	MI	HSSF	Lab	S	1 d	10	47.3	31.9	56.1	NA	(Chong et al., 2012)
	Benthos	HSSF	Lab	S	13 d	1-6	NA	56.9	85.1	NA	(Kang et al., 2016)
Operating condition	Batch	VSSF	Lab	D	24 h-12 h	5-10	81.1	85.6	48.4	NA	(Zhou et al., 2007)
	Batch	HSSF	Pilot	D	12 h-12 h	8-10	95.1	74.4	78.7	NA	(Zhang et al., 2012)
Integra-tion	Hybrid CW	-	Full	F	NA	6.4	77.7	78.2	85.5	74.9	(Harada et al., 2015)
	Hybrid CW	-	Pilot	M	13 h-33 h	1-17	88-91	92-98	51.4	67-77	(Wang et al., 2017)
	Green-house	HSSF	Full	D	4 h–35 h	2-5	85	70.98	NA	36.5	(Gao and Hu, 2012)
	Algal pond	VSSF	Lab	S	5 d	5-10	70.3	NA	81	71.9	(Zhao et al., 2016)

MI indicates microbial inoculant. W means wastewater type including raw (R), town (T), domestic (D), synthetic (S), farm (F), municipal (M) wastewater. T is the temperature.

Declarations

No conflict of interest, informed consent, human or animal rights were applied.

- Microbial activity is main restrictive factor on CW operation at low temperatures.
- Mutation breeding and nanomaterial provide a choice for CW sustainable development.
- CW combined other treatment processes to remove specific pollutants is a trend.