An overview of methane emissions in constructed wetlands: how do plants influence methane flux during the wastewater treatment?

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ABSTRACT
Plants play an essential role in methane (CH₄) production, transport and release processes of constructed wetlands but as yet there has been no consistent and clear consensus of their impacts on CH₄ emissions. In this study, we used plant presence, species richness, plant species-specificity, and harvesting activity information obtained by reviewing papers published from 1993 to 2018 to elucidate the key factors that drive CH₄ emission from constructed wetlands. Although it was not statistically significant, plant presence increased the CH₄ emissions compared to unvegetated conditions and relatively lower values were observed for constructed wetlands planted with Acorus calamus, Cyperus papyrus or Juncus effusus. The use of a single plant species not only changed the production and consumption of CH₄ by affecting the functioning of roots but also influenced the process of CH₄ entering the atmosphere under different transport capacities. The CH₄ flux reached 1.0686 g CH₄ m⁻² d⁻¹ from the Zizania latifolia system, which is eight times larger than that of the Phalaris arundinacea system. The mixed systems exhibited a positive increase in CH₄ flux with plant species richness due to the complementary effects of the root exudates excreted from different plants. The minimum CH₄ value (~0.0084 g CH₄ m⁻² d⁻¹) was observed in the three-species system (Oenanthe javanica, Phalaris arundinacea and J. effusus). These results demonstrate that selecting several species with lower methane fluxes such as Typha latifolia and C. papyrus and suitably regulating harvesting in constructed wetlands can be more effective for mitigating the potential of CH₄ emissions while maintaining the efficiency of sewage purification.

Introduction

Constructed wetlands that are easy to operate and maintain are an ideal alternative to typical wastewater treatment technologies (Garcia et al. 2010; Mitsch et al. 2014). They have
been used increasingly for treating various types of wastewater, such as municipal, domestic, and agricultural wastewater (Wu et al. 2015). The number of constructed wetlands in China has exponentially increased from less than 10 to over 400 in the last two decades (Zhang et al. 2012a; Li et al. 2018). Meanwhile, previous studies have demonstrated that the areas converted to wetlands will likely result in dramatic increases in CH₄ emissions (Johansson et al. 2004). Hence, the large increase in constructed wetland areas has raised environmental concerns owing to the potential increase in the emissions of CH₄, despite their potential ability to control pollutants (Xue et al. 1999; Niu et al. 2015).

According to some previous studies, the surface dry air molar fraction of atmospheric CH₄ in 2012 reached 1810 ppb, which is 2.5 times larger than it was in 1750 (Kirschke et al. 2013). Owing to the sustained rise in atmospheric CH₄ levels, CH₄ has gradually become the second most important anthropogenic greenhouse gas after CO₂ (Nouchi et al. 1994; Saunois et al. 2016). A large number of experimental papers on CH₄ fluxes in constructed wetlands have been published, indicating that the wastewater treatment process plays an extremely important role in the various CH₄ sources (IPCC 2014).

During the sewage purification process in constructed wetlands, plants are one of the most significant factors affecting CH₄ emission because of their roots and stem systems (Segers 1998; Ström et al. 2005; Wang et al. 2008; Lai et al. 2011; Mander et al. 2014) that release oxygen and produce root exudates (Jackson and Armstrong 1999; Saarnio et al. 2004). CH₄ fluxes are determined by the balance between the formation and consumption of CH₄ (Wang et al. 2013a). The most frequently used plant in constructed wetlands worldwide is Phragmites australis, while Typha latifolia, Juncus effusus, Phalaris arundinacea, and Zizania latifolia are also commonly used. However, there have been no uniform results regarding the effect of plants on CH₄ flux.

Phragmites australis is the most frequently used macrophyte in constructed wetlands, as it can form a monoculture and significantly modify the structure and functions of wetland ecosystems (McCormick et al. 2010; Uddin et al. 2017). The aboveground parts of P. australis die back at the end of the annual growth cycle but the underground parts remain viable for many years. Its physiological characteristics including high reproductive rate, well-developed aerated tissue, a rhizosphere that promotes colonization, and dense canopy associated with high productivity that can inhibit germination and growth of other plant species (Meyerson et al. 2000; Mozdzer and Zieman 2010; Guo et al. 2013). Greater biomass and different decomposition rates can cause changes in the CH₄ flux in P. australis-based constructed wetlands.

Zizania latifolia is a well-known wild rice grass. As a perennial, herbaceous aquatic plant (Wang et al. 2014), it commonly grows to 1.5–3.0 m with well-developed fibrous roots usually in swampy regions and wetlands, normally alongside some emergent plants, such as T. angustifolia and P. australis.

Typha latifolia (commonly called broadleaf cattail) is a well-known aquatic wetland plant that grows widely in tropical and warm regions, including Asia, Africa, the Americas, and Europe (Ye et al. 1997; Ahmad et al. 2017). This species can expand to areas that were previously occupied by other species owing to their size, adaptability, and root exudates (Gallardo et al. 1998). Typha latifolia can quickly inhabit poor environments and has strong environmental adaptability (He et al. 2015).

Juncus effusus, which has cylindrical photosynthetic stems filled with a spongy pith, is widely used in sewage treatment and the stimulation of microbial activity (Moran and Hodson 1989; Garnet et al. 2005). It has since been established as a model plant in basic and applied research on wetland ecosystems.
Phalaris arundinacea is a 1–3 m-high perennial herb that produces dense crowns and forms a strong root system that penetrates to depths of approximately 30–40 cm and spreads aggressively by asexual reproduction (Lewandowski et al. 2003). It is generally best suited for growth under cool and moist conditions, tending to form a single cultivar by inhibiting the growth of other plants (Lavergne and Molofsky 2004; Adams and Galatowitsch 2005). Studies have reported that P. arundinacea has more developed above-ground parts relative to its roots under enhanced pollutant treatment (Maurer and Zedler 2002).

The presence of aquatic plants is one of the most significant features of wetlands, and it distinguishes constructed wetlands from unvegetated traditional sewage treatment methods (Vymazal 2011). Many researchers have studied several plant factors that affect CH₄ fluxes in constructed wetlands (Wang et al. 2008; Zhang et al. 2012b; Mander et al. 2014). Accordingly, to explore the plant factors that drive CH₄ fluxes, we reviewed articles published from 1993 to 2018 to investigate the fluxes in various constructed wetlands by comparing plant conditions. Does the presence of plants inhibit methane emissions? Does the species richness facilitate methane emissions? Does the selected species increase the ecological effects of wetlands? Does harvesting reduce methane emissions?

**Methods**

**Data collection**

A literature survey of peer-reviewed publications published in the last 25 years (1993-2018) on constructed wetlands and CH₄ flux was conducted. The terms ‘(aquatic) plant/macrophyte’, ‘methane (CH₄)’, ‘methanogens’, and ‘methanotrophs’, in combination with the terms ‘(artificial/constructed/treatment) wetland’ were searched using ISI-Web of Science. We selected papers that focused on the factors that were most likely to affect CH₄ flux, including (1) plant presence, (2) plant species, (3) plant species richness, and (4) plant harvesting. After manually eliminating less relevant works from 317 articles, 129 remaining papers were selected for further investigation. Data were collected from 62 studies conducted on 23 constructed wetlands from 15 countries that discussed plants as a prominent factor affecting CH₄ flux in constructed wetlands (Figure 1). Some of the data were excluded as they were greatly affected by other factors, such as water level, season, and peatland.
Data analysis

The collected data were divided into two categories according to the source of water (sewage and modified Hoagland nutrient solution; Hoagland and Arnon 1950). The Hoagland nutrient solution can meet the trace element needs of the plant growth process while preventing its influence on the determination of root exudates (Table 1). In sewage-based constructed wetlands, the data were more likely to show the effects of plant species on CH4 fluxes, while the other data with the modified Hoagland nutrient solution were more likely to indicate the effects of plant species richness on CH4 fluxes. Furthermore, there are seasonal and daily variations in CH4 fluxes. We mainly selected data for similar seasons and took the average to minimize the error. All CH4 flux data were expressed using Origin 9.0.

An independent samples t-test was conducted to determine the differences between the vegetated and unvegetated systems using SPSS Statistics 20 (SPSS Inc., Chicago, USA). One-way analysis of variance (ANOVA) was also conducted to test the differences between the mean values when different species were present in the communities. The statistical significance level was set at $\alpha = 0.05$.

Results

The number of papers published from 1993 to 2018 on CH4 fluxes in constructed wetlands increased every 5-year period (Figure 2a). In particular, in recent years, the number of relevant studies is almost at a high level. Most data about CH4 emissions were obtained from laboratory and actual constructed wetlands field studies published in the last 10 years. The planting density of seedlings with similar sizes benefitting their survival was 9–16 individuals per microcosm. From analyzing the data from 62 papers of the 317 studies, 20 plant species were recorded. The most common plants used in constructed wetlands are P. australis (35.29%), T. latifolia (17.65%), J. effusus (8.82%), P. arundinacea (7.84%) and Z. latifolia (5.88%) (Figure 2b).

| Macroelement | g L$^{-1}$ | Macroelement | g L$^{-1}$ |
|--------------|------------|--------------|------------|
| KNO$_3$      | 1.46       | H$_2$BO$_3$  | 2.86       |
| Ca(NO$_3$)$_2$·4H$_2$O | 1.13 | MnCl$_2$·4H$_2$O | 1.81 |
| CaCl$_2$·2H$_2$O | 0.50 | ZnSO$_4$·7H$_2$O | 0.22 |
| KH$_2$PO$_4$ | 0.14       | CuSO$_4$·5H$_2$O | 0.08       |
| MgSO$_4$·7H$_2$O | 0.49 | H$_2$MoO$_4$·4H$_2$O | 0.09 |
| KCl          | 0.09       | FeSO$_4$·7H$_2$O | 5.56 |
|              |            | Na$_2$EDTA   | 7.44       |

Plant presence

The methane flux did not exhibit a statistically significant difference, although the flux was higher for vegetated systems (mean of 0.424 g CH$_4$ m$^{-2}$ d$^{-1}$) than that of unvegetated systems (mean of 0.254 g CH$_4$ m$^{-2}$ d$^{-1}$) with sewage ($p = 0.089$). The range of CH$_4$ emissions from vegetated systems (0.0236 to 2.208 g CH$_4$ m$^{-2}$ d$^{-1}$) was larger than that from unvegetated systems (−0.0048 to 0.9192 g CH$_4$ m$^{-2}$ d$^{-1}$) when treating sewage (Figure 3a). The highest CH$_4$ emission value was observed in the Z. latifolia system, while relatively lower values were observed in constructed wetlands planted with Acorus calamus, C. papyrus, or J. effusus. As shown in Figure 3b, the methane flux was also similar.
between vegetated systems (mean of 0.0046 g CH$_4$ m$^{-2}$ d$^{-1}$) and unvegetated systems (mean of 0.0036 g CH$_4$ m$^{-2}$ d$^{-1}$) with the modified Hoagland nutrient pollution, as indicated by analyzing the data ($p = 0.831$). The maximum and minimum fluxes were recorded in a polyculture system (Rumex japonicas, Oenanthe hookeri, P. arundinacea and J. effusus) and a monoculture (J. effusus) system, respectively.

The effects of species-specific relationships on CH$_4$ flux

In our study, significant differences were observed between different plant species in sewage systems ($F = 2.99$, $p = 0.004$, Figure 4a). The highest CH$_4$ emission values were observed for Z. latifolia constructed wetlands (mean of 1.069 g CH$_4$ m$^{-2}$ d$^{-1}$), followed by J. effusus and P. australis (means of 0.528 and 0.523 g CH$_4$ m$^{-2}$ d$^{-1}$, respectively).
Compared to unvegetated systems, the systems planted with vascular plants, such as *P. arundinacea*, *C. papyrus*, or *T. latifolia*, exhibited lower CH$_4$ fluxes into the atmosphere. These species are suitable for mitigating the greenhouse effect in the operation of constructed wetlands. Meanwhile, the CH$_4$ flux (ranging from 0.0024 to 0.0065 g CH$_4$ m$^{-2}$ d$^{-1}$) did not differ significantly between different plant species ($F = 1.652$, $p = 0.182$), but the relatively low CH$_4$ fluxes of approximately 0.0024 g CH$_4$ m$^{-2}$ d$^{-1}$ were observed in *P. arundinacea* systems with the modified Hoagland nutrient solution (Figure 4b). The maximum value was only 0.0089 g CH$_4$ m$^{-2}$ d$^{-1}$. This may be because the effect of transportation on CH$_4$ emissions through the aerenchyma of plants is not fully exerted with low concentrations of biodegradable organic matter in wastewater.

**Species richness**

The number of species in a plant community is referred to as the species richness. In this study, the CH$_4$ flux increased with species richness during wastewater treatment in...
constructed wetlands, thus confirming that species richness was a factor affecting CH₄ emissions. Regardless of the magnitude of methane emissions, the overall trend in methane flux is increasing with species richness. When the inflow is the modified Hoagland nutrient solution, the increasing CH₄ flux value may be small, but the increasing trend with plant species richness is clear (Figure 5). Although, plant species richness had almost no effect on CH₄ emissions when the water had high nitrogen levels. It was noteworthy that the minimum methane value (−0.0084 g CH₄ m⁻² d⁻¹) was observed in a three-species system (O. javanica, P. arundinacea, and J. effusus). However, limited relevant experimental studies on sewage-based constructed wetlands indicated that a high

Figure 4. CH₄ flux from constructed wetlands with different species (a) sewage. Others include Arundo donax, Canna indica, Glyceria maxima, Miscanthus giganteus; (b) modified Hoagland nutrient solution. Boxes show median and interquartile range. Outliers are identified as points outside 1.5 times the interquartile range.
species richness was beneficial for CH$_4$ emissions. In the polyculture system, the maximum CH$_4$ emission value reached 5.88 g CH$_4$ m$^{-2}$ d$^{-1}$, which is about 2.27 times larger than that in the monoculture system (2.592 g CH$_4$ m$^{-2}$ d$^{-1}$).

**Plant harvest on CH$_4$ emission**

The production and consumption of CH$_4$ in wetlands are affected by the growth stage of plants and the net primary productivity of the ecosystem (Whiting and Chanton 1993; Hanson and Hanson 1996). The CH$_4$ flux was influenced remarkably by plant harvesting, and it occurred immediately after the plants in the constructed wetlands were harvested (CH$_4$ emissions were reduced by a factor of 12). The CH$_4$ emissions were found to recover 0.0008 g CH$_4$ m$^{-2}$ d$^{-1}$.

**Discussion**

Methane appears to be the most important GHG emitted from constructed wetlands (Maltais-Landry et al. 2009; Mander et al. 2014). The flux of CH$_4$ is affected by various factors including the age of constructed wetlands (Liikanen et al. 2006; Zemanová et al. 2010; de la Varga et al. 2015), wastewater flow (Liu et al. 2009) and quality (Yan et al. 2012), feeding schemes (Jia et al. 2011) and environmental conditions (Liikanen et al. 2006). Meanwhile, a more detailed biogeochemical cycle can be learned from Megonigal’s article (Megonigal and Neubauer 2019). Special attention should be paid to the plant species used in constructed wetlands, which heavily affect the CH$_4$ flux from constructed wetlands by influencing microbial activity (Inamori et al. 2007). In general, the methane emitted to the atmosphere experiences the three processes of production, consumption and transport (Figure 6). For production, plants provide an appropriate root surface and exudates for the growth and activity of microorganisms (Zhai et al. 2013), promoting the conversion of organic matter to CH$_4$ (anoxic zone). Subsequently, the amount of oxygen released by root systems into the sediment would enhance the number of methanotrophs as they favor the aerobic rhizosphere environment. The transport process in the emission

![Figure 5. CH$_4$ flux with different plant species richness levels in modified Hoagland nutrient solution constructed wetlands.](image-url)
of CH$_4$ is also crucial for the contribution of the quantity of atmospheric CH$_4$. The CH$_4$ flux emitted to the atmosphere in vascular plant-dominated constructed wetlands is primarily driven by three processes including ebullition and diffusion, and plant emissions (Brix et al. 2001). However, more CH$_4$ would be oxidized in the first two processes than in plant-mediated transport through the aerenchyma resulting in a large CH$_4$ flux from planted constructed wetlands. Furthermore, both electron donors and acceptors play important roles in regulating anaerobic microbial mineralization of soil organic matter (Sutton-Grier et al. 2011). The final CH$_4$ flux in vegetated or unvegetated constructed wetlands is determined by the combined effects of plants on CH$_4$ production, transport, and consumption. The effect of plants on CH$_4$ emission is remarkable, and requires further study. Therefore, we reviewed published literature to evaluate the effects of different plant species on CH$_4$ emissions.

**Plant presence**

The role of plants in constructed wetlands is crucial (Vymazal 2011). Most studies clearly demonstrated that constructed wetlands with plants have better pollutant removal efficiencies than those without (Vymazal 2011) and they have a significant effect on CH$_4$ fluxes during the pollutant removal process (Henneberg et al. 2016). Although there was no significant difference between vegetated and unvegetated constructed wetlands, vegetated systems exhibited a higher average CH$_4$ flux in vegetated systems than that of unvegetated systems. Previous studies support this trend, demonstrating that the presence of plants increases CH$_4$ fluxes in constructed wetlands (Wild et al. 2001; Ström et al. 2007). McInerney and Helton (2016) observed higher CH$_4$ emissions from vegetated constructed wetlands by comparing the presence and absence of emergent herbaceous vegetation (*T. angustifolia* and *T. latifolia*). Recently, Wu et al. (2017) continuously measured the flux of CH$_4$ from free-water surface-constructed wetlands in northern China following the static-stationary chamber technique from 2012 to 2013, and observed higher CH$_4$ emissions from planted wetlands than those from unplanted systems. Similarly, Wang et al. (2013a)
found that the CH$_4$ flux of vegetated systems (1.6752 g CH$_4$ m$^{-2}$ d$^{-1}$) is much higher than that of unvegetated systems (0.276 g CH$_4$ m$^{-2}$ d$^{-1}$). Similar results were also obtained by Niu et al. (2015), who reported that a vegetated system achieved a higher CH$_4$ flux rate than an unvegetated system. Therefore, the presence of plants would boost the CH$_4$ flux while increasing the pollutant removal efficiency. A greater amount of methanogens are found in vegetated constructed wetlands as plants provide a more beneficial environment for their growth and reproduction, such as their large root surfaces and carbon sources (Zhai et al. 2013), resulting in a high level of methane production. The aerenchyma contained inside plants facilitates the transport of methane from soils or water to the atmosphere (Terazewa et al. 2007; Rice et al. 2010). It has been reported that up to 95% of the CH$_4$ emissions of vegetated wetlands may be transported through the aerenchyma (Schütz et al. 1989; Grünfeld and Brix 1999; Bhullar et al. 2013), and this pathway can reduce both the ebullition and diffusion of CH$_4$ through the soil column (Sorrell and Boon 1994; Schimel 1995). Although the roots may modify the soil oxidation-reduction potential due to the release of oxygen, which may mitigate the CH$_4$ flux, it was not decisive. Only a few studies stated that unplanted conditions have a higher CH$_4$ flux than planted systems (Grünfeld and Brix 1999; Zhu et al. 2007; Maltais-Landry et al. 2009; Bateganya et al. 2015). Bateganya et al. (2015) observed higher CH$_4$ emissions from unplanted beds (0.624 g CH$_4$ m$^{-2}$ d$^{-1}$) than that from planted beds (C. papyrus) (0.312 g CH$_4$ m$^{-2}$ d$^{-1}$) for both vertical and horizontal subsurface flow constructed wetlands. However, de la Varga et al. (2015) and Maucieri et al. (2014) did not observe any significant differences in CH$_4$ emissions between vegetated and unvegetated constructed wetlands. This might be due to the greater soil oxidation-reduction potential status in certain constructed wetlands, which inhibits methane emissions. Artificial aeration, the construction of intermittent vertical subsurface flow constructed wetlands, or wetland plants with strong oxygen capacity can all achieve this (Maltais-Landry et al. 2009; Bateganya et al. 2015). The abundant methanotrophics bacteria inhabiting aerobic regions can promote the oxidation of the large quantities of produced CH$_4$ (Schütz et al. 1989; Denier van der Gon and Neue 1996).

In summary, the flux of CH$_4$ from constructed wetlands is positively related to the presence of plants in most case. The main reason for this is that CH$_4$ emission conditions are optimized by the physiological functions of plants in constructed wetlands.

**The effects of plant species on CH$_4$ flux**

Most recent studies focused on the influence of plant species on CH$_4$ flux (Barbera et al. 2015; Cao et al. 2017). Aquatic macrophytes can have different anatomical and physiological properties (Zhang et al. 2011), and their diversity has a remarkable effect on the CH$_4$ flux. Owing to the ability of plants to raise the sediment redox potential, the release of root exudate and transport capacity correlate with the ability of the macrophytes to influence the CH$_4$ flux (van der Nat and Middelburg 1998; Wang et al. 2008; Duan et al. 2009; Wang et al. 2013a; Girkin et al. 2018). Until now, significant differences in CH$_4$ emissions were observed between constructed wetlands with different plant species. Considering the difference in plant species, such as *P. arundinacea* and *Z. latifolia*, their degree of influence in methane flux would be different. Markedly higher CH$_4$ emissions from *Z. latifolia* constructed wetland than those from *P. arundinacea* wetlands have been observed. The plant species determines the release of root exudates and oxygen, and the capacity of transport, which indirectly highlights the specific effects of plant species on the CH$_4$ flux due to the variation in the biogeochemical processes involved in organic
matter degradation (Brix et al. 1992; Malais-Landry et al. 2009). Most researchers have studied the plant species-specific effects on methane emissions and have monitored the differences in methane emission fluxes of constructed wetlands with different plants, such as *Z. latifolia*, *P. australis* and *T. latifolia* (Inamori et al. 2007; Ström et al. 2007; Wang et al. 2008; Barbera et al. 2015; Wu et al. 2017).

Understanding plant physiology might be useful in estimating CH$_4$ emissions, as CH$_4$ emissions vary between plant species and functional traits. For example, *P. australis* has an extensive rhizome system that usually penetrates to depths of approximately 0.6–1.0 m, and rigid stems with hollow internodes. Consequently, oxidation-reduction potential values of *P. australis* systems are higher than those of *Z. latifolia* systems at the same BOD concentration. This may explain the lower methane emissions observed from *P. australis* systems (Inamori et al. 2007). In this article, CH$_4$ emissions were found to be significantly higher from *Z. latifolia* than those from some other species, which a potential benefit of using some monospecific stands for constructed wetlands. Furthermore, *P. arundinacea*, *C. papyrus*, or *T. latifolia* might be the best choice for reducing the CH$_4$ flux during the sewage treatment process of constructed wetlands.

The authors have suggested that oxygen transfer, CH$_4$ transfer, and root exudate release capacities vary between plant species, confirming the species-specific effects on CH$_4$ emissions (Inamori et al. 2007; Ström et al. 2007; Wang et al. 2008; Barbera et al. 2015; Wu et al. 2017). Therefore, selecting an adequate plant species can modify the microbial processes of constructed wetlands and change (promote or inhibit) the CH$_4$ formation, oxidation, and transport processes, subsequently changing the level of CH$_4$ emissions (Wang et al. 2008). Remarkably, the rhizosphere is a key zone for CH$_4$ formation and oxidation as it determines the quantity and activity of methanogens and methanotrophs during pollutant removal in constructed wetlands. Roots release a degradable substrate as a carbon source that would increase the number of methanogens and methanotrophs during pollutant removal in constructed wetlands. Roots release a degradable substrate as a carbon source that would increase the number of methanogens and methanotrophs (Wang et al. 2013b). For example, Inamori et al. (2007) found that 90% of the root biomass was concentrated in the top 10 cm of the substrate in vertical subsurface flow constructed wetlands vegetated with *Z. latifolia*, while the root biomass extends deeper and is evenly distributed along the substrate profile in *P. australis* systems. Meanwhile, it has been reported that methanotrophs are mainly distributed in the first 10 cm and then decrease along the depth of the rhizosphere in *Z. latifolia* systems. However, *P. australis* systems showed that bacteria are mainly distributed in the deeper layers (20 and 30 cm) rather than the first 10 cm due to the effects of activities involving plant roots. However, plant species that have a high biomass and dense root system may exude more organic matter, promoting the growth and reproduction of CH$_4$-oxidizing bacteria and methanogens (Wang et al. 2013a). For CH$_4$ production, the quantity of organic matter determined the growth of microbial bacteria, rather than the chemical characteristics of the substrate, which are similar between different plants. Therefore, the species-specific effects of plants are an important factor causing the CH$_4$ flux to vary. The release of oxygen by plant root systems creates an aerobic microsite favored by methanotrophs that grow in the process of CH$_4$ consumption (Wang et al. 2008). Many studies suggested that oxygen release is greater from some plants that have a higher aboveground biomass, such as *Phragmites* sp., than that of *Typha* sp. and *Iris* sp. (Wießner et al. 2002; Wang et al. 2009). However, the aerenchyma of a plant not only can play a significant role in the transportation of CH$_4$ from wetlands to the atmosphere, but it also enables the transportation of oxygen from the air to the underground parts of the plants (Chanton et al. 1993; Rusch and Rennenberg 1998; Laanbroek 2010). For example, increased oxygen input from plants with greater biomass can offset any potential
stimulation of methanogenic microbes from additional carbon inputs. Because the species composition of plant communities influences both electron donor and acceptor availability in wetland soils, changes in plant species as a consequence of anthropogenic disturbance have the potential to trigger profound effects on microbial processes, including changes in anaerobic decomposition rates and the proportion of mineralized carbon emitted as the greenhouse gas methane (Sutton-Grier and Megonigal 2011). Therefore, the differences in the transport function between different plant species in the CH₄ emission process are noteworthy. In summary, through reviewing associated papers, the structure and physiological function of different plant species were found to be closely related to CH₄ emissions.

**Plant species richness**

Hybrid plants generally elevate the CH₄ flux to a certain extent, although the effect is small at high nitrogen levels. Our finding was most likely attributed to the complementary effect of the root exudates excreted from the different plants in polyculture systems. Zhang et al. (2012b) found that the CH₄ flux increased significantly with an increase in the plant species richness (O. hookeri, R. japonicus, P. arundinacea and Reineckia carnea). Wang et al. (2013a), compared a Z. latifolia monoculture system with a polyculture planted with Z. latifolia, P. australis and T. latifolia, and observed a higher CH₄ flux in the polyculture system (mean of 2.208 g CH₄ m⁻² d⁻¹) than that in the monoculture system (mean of 1.1424 g CH₄ m⁻² d⁻¹), with the lowest emissions in the senescence period and highest emissions during growth season. In the same year, Wang et al. (2013b) concluded that CH₄ emissions could be stimulated in polyculture systems. The results reported by Niu et al. (2015) agreed with those of the previously mentioned study, indicating that a higher CH₄ flux was observed in the mixed system (R. japonicus, O hookeri, P. arundinacea and J. effusus) than that in the monoculture due to the higher abundance of methanogens and lower number of methanotrophs.

In polyculture systems, the plant biomass increases with the plant species richness due to the complementary use of plants for nutrients in diverse species communities (van Ruijven and Berendse 2003; Zhang et al. 2011). The plant biomass increased with the plant species richness in these microcosms, which further lead to an increase in microbial biomass. Furthermore, the increased microbial biomass promoted the degradation of organic matter around the rhizosphere (Zhang et al. 2012a, b; Zhao et al. 2016a,b). Therefore, a higher number of methanogens and lower number of methanotrophs were observed in the rhizosphere regions of polyculture systems, resulting in large contributions to CH₄ generation. Moreover, the more-developed aeration tissue increased the emission of CH₄ with increasing plant species richness.

Han et al. (2017) used four common local plant species (J. effusus, O. javanica, P. arundinacea and R. japonicus) in a microcosm experiment and found that plant species richness had no effect on CH₄ flux. Furthermore, Mo et al. (2015) and Zhao et al. (2016a) also investigated the effect of plant species richness on the CH₄ flux in constructed wetlands, and observed no significant relationship between plant species richness and CH₄ flux. This is most likely due to the weak complementarity of some plant species, resulting in little effects on the CH₄ flux.

So far, most researchers have observed a positive correlation between CH₄ flux and plant species richness (Zhang et al. 2012b; Niu et al. 2015), while a few studies reported that CH₄ flux was not affected by species richness in constructed wetlands (Zhao et al. 2016a; Han et al. 2017). This might be due to the diversity of plants during the
experiment, which changed the quantity and activity of microbes by affecting the conditions in the constructed wetlands (Wang et al. 2012). However, different environmental factors, such as temperature, oxidation-reduction potential, ratio of C/N and water level, also played roles in the relationship between plant species richness and CH$_4$ flux (Henneberg et al. 2016). Under these scenarios, the quantities of microbial bacteria were affected, resulting in different CH$_4$ flux levels, and the effect of plant species richness on CH$_4$ flux was greatly weakened.

**The influence of plant harvesting**

Although the physiological and structural characteristics of plants significantly affected the CH$_4$ flux, the effect of plant harvesting on CH$_4$ emissions from wetlands to the atmosphere cannot be ignored. Zhu et al. (2007) found that CH$_4$ emissions increased immediately after cutting *P. communis* in both free water-surface and horizontal subsurface-flow systems, which is likely due to the rapid release of the CH$_4$ retained in the vascular systems of plant stems. After a few days, the CH$_4$ flux from constructed wetlands was still higher in plant-harvested regions than un-cut zones as the stems above the water surface still served as conduits for constructed wetlands bed gases until the stem butts died. In agreement, higher CH$_4$ emissions from horizontal subsurface flow constructed wetlands vegetated with *M. giganteus* were observed after plant cutting by Barbera et al. (2015), and from horizontal and vertical subsurface flow constructed wetlands vegetated with *P. australis* and *Arundo donax* by Maucieri et al. (2016).

After harvesting the plants, the CH$_4$ stored in their stems releases to the atmosphere within a short period of time, and the transport of CH$_4$ through the aerenchyma is still a viable mechanism of releasing CH$_4$ into the atmosphere from constructed wetlands. In addition, the physiological activities that release exudate and oxygen through the root systems during sewage purification would disappear with the harvesting of plants, and the number of methanotrophs would significantly decrease due to the smaller aerobic rhizosphere environment. These factors contribute to the emission of CH$_4$ until the roots rot. Subsequently, owing to the disappearance of plants, similar CH$_4$ emission fluxes would be observed in vegetated and unvegetated constructed wetlands. Similarly, controlled harvesting in free water-surface and horizontal subsurface-flow constructed wetlands can minimize CH$_4$ emissions.

**Conclusion**

Methane fluxes are only slightly higher in vegetated constructed wetlands than those in unvegetated constructed wetlands while obtaining a better pollutant removal efficiency. The emission of CH$_4$ is significantly influenced by plant specific-species factors during the operation of constructed wetlands, especially *Z. latifolia* systems, which emit more CH$_4$ than systems with other plant species. Overall, the CH$_4$ flux increases with species richness; however, there is also a special scenario in which the lowest CH$_4$ flux was observed in the three-species system (*O. javanica, P. arundinacea* and *J. effusus*). Additionally, no significant result has been observed regarding the effect of plant harvesting on CH$_4$ emissions. Further research on selecting an optimal plant and harvest management in constructed wetlands are required to effectively reduce the emissions of CH$_4$. It is worth noting that the release of root oxygen and exudates, and the mediating function of plants could be used as a parameter for selecting wetland plants when assessing greenhouse gas budgets.
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