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Review

Removal of non-point source pollutants from domestic sewage and agricultural runoff by vegetated drainage ditches (VDDs): Design, mechanism, management strategies, and future directions

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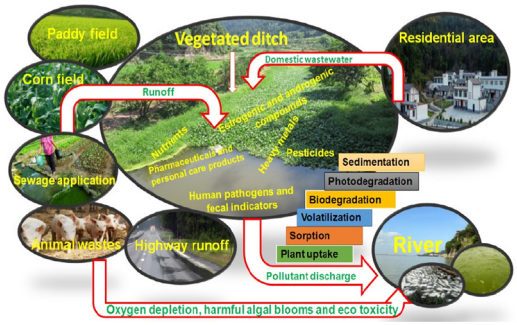
HIGHLIGHTS

- We review the application of VDDs for nutrient and organic pollutant removal.
- We summarize the major ruling ditch characteristics of documented ditches.
- VDDs can remove nutrients and organic pollutants through various pathways.
- Plants, substrate, and microbes in ditches account for the primary removal mechanisms.
- Further research is required to fill knowledge gaps on VDD maintenance.

GRAPHICAL ABSTRACT



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ABSTRACT

Domestic wastewater and agricultural runoff are increasingly viewed as major threats to both aquatic and terrestrial ecosystems due to the introduction of non-point source inorganic (e.g., nitrogen, phosphorus and metals) and organic (e.g., pesticides and pharmaceutical residues) pollutants. With rapid economic growth and social change in rural regions, it is important to examine the treatment systems in rural and remote areas for high efficiency, low running costs, and minimal maintenance in order to minimize its influence on water bodies and biodiversity. Recently, the use of vegetated drainage ditches (VDDs) has been employed in treatment of domestic sewage and agricultural runoff, but information on the performance of VDDs for treating these pollutants with various new management practices is still not sufficiently summarized. This paper aims to outline and review current knowledge related to the use of VDDs in mitigating these pollutants from domestic sewage and agricultural runoff. Literature analysis has suggested that further research should be carried out to improve ditch characteristics and management strategies inside ditches in order to ensure their effectiveness. Firstly, the reported major ditch characteristics with the most effect on pollutant removal processes (e.g., plant species, weirs, biofilms, and substrates selection) were summarized. The second focus concerns the function of ditch characteristics in VDDs for pollutant removal and identification of possible removal mechanisms involved. Thirdly, we

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examined factors to consider for establishing appropriate management strategies within ditches and how these could influence the whole ditch design process. The current review promotes areas where future research is needed and highlights clear and sufficient evidence regarding performance and application of this overlooked ditch system to reduce pollutants.

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1. Introduction

In recent years, with rapid socio-economic development, environmental conditions are dramatically changing in many rural regions of developing countries (Jin et al., 2018; Ongley et al., 2010; USEPA, 2003; Zheng and Wang, 2002). As a result, non-point source inorganic pollutants [e.g., nitrogen (N), phosphorus (P), sediments and metals], and organic pollutants (e.g., pesticides and pharmaceutical residues), human pathogens and estrogenic and androgenic compounds, including those from untreated domestic sewage and agricultural sources (i.e., agricultural land, manure, animal feedlots and aquaculture), have polluted rivers, lakes, and reservoirs (Alexander et al., 2008; Carpenter et al., 1998; Davis and Koop, 2006; Edwards et al., 2009; Gall et al., 2011; Kumwimba et al., 2017a; Moeder et al., 2017; Ongley et al., 2010; Schijven et al., 2015; Tran et al., 2015; Toet et al., 2005). According to the First National Survey of Pollution Sources Bulletin of China (Zhang, 2010), rural non-point source pollution includes approximately half of the total water pollution, accounting for 57% of the total N and 67% of the total P. Thus, mitigation of non-point source pollution is critical in rural regions in the coming years (Qiu, 2011). In most rural and remote regions, these pollutants are discharged directly into surface-receiving waters without treatment due to the lack of wastewater treatment facilities. Considering technological and economic issues (i.e., low rate of economic development, power shortage, and lack of skilled employees) in rural and remote zones in developing countries, attention has shifted to assessing the effectiveness of pollutant removal in ecological engineering systems [(e.g., constructed wetlands CWs), floating islands, retention basins, riparian buffer vegetation, and stiff grass hedges] (Cooper et al., 2004, Kröger et al., 2007a, 2008a; Kröger and Moore, 2011, Moore et al., 2000, 2006, Needelman et al., 2007). Scientists and land managers now promote the utilization of vegetated ditches (VDDs) as an additional best management practice (BMP) for pollutant mitigation (Bennett et al., 2005; Cooper et al., 2004; Kumwimba and Zhu, 2017; Kröger et al., 2008a; Sharpley et al., 2007; Vallée et al., 2014). They require less land area, which is important in the plains area of many countries, particularly the United States and China, where land is valuable. Drainage ditches are also unique ecosystems, having the features of both streams and wetlands (Moore et al., 2001a, 2001b).

Drainage ditches are fundamentally similar to free water surface wetlands (e.g., hydroperiod, hydric soils, and hydrophytes). They are referred to as ecotones between land and surface receiving waters (Ahiablame et al., 2010; Herzon and Helenius, 2008; Kumwimba et al., 2017b; Moore et al., 2001a, 2005). Depending on the circumstance, they may function as a sink, source, or regulator of nutrients, metals, pesticides, and other agricultural pollutants to adjacent water bodies (Kladivko et al., 1999; Kumwimba et al. 2016a, d; Moeder et al., 2017; Moore et al., 2001a, 2001b; Needelman et al., 2007; Randall and Vetsch, 2005; Tomer et al., 2003; Zhu et al., 2012). Because of the sediment and plants within VDDs, a distinctive sediment-aquatic plant-microbial system is built, and complex physical, chemical, and biological processes occur for pollutant degradation in the system.

Neglected in the past for their value, function and mitigation capabilities, VDDs have tremendous potential to mitigate a broader range of pollutants in a way comparable to CWs, including intercepting and purifying runoff pollution from different land uses before entering water bodies. More recently, there has been increased interest in promoting the utilization of ditches for water quality and environmental benefits

in the Netherlands, Great Britain and Finland. For example, in the US, VDDs are BMPs for their nutrient and pesticide retention (Cooper et al., 2004; Dabney et al., 2006; Fouss and Sullivan, 2009; Kröger et al., 2013; Moore et al., 2001a, 2001b). These systems consist of flow control structures, water discharge channels, substrates, vegetation, and periphytic microorganisms for contaminant treatment (Wu et al., 2013). When well-managed, VDDs have a wide range of ecosystem benefits, e.g., preventing waterlogging, controlling soil erosion, water purification, biodiversity conservation and rehabilitation, groundwater recharges, and flood prevention (Fig. S1) (Dollinger et al., 2015; Kumwimba et al., 2017d). Nevertheless, it is important to emphasize that the pollutant mitigation capacity of VDDs and the sustainable operation over the long-term, are increasingly seen as a major future challenge. On one hand, ditch characteristics (size, length, slope, vegetation cover and types) and bed properties (soil media types) are primary factors influencing the mitigation capacity within ditch systems (Kumwimba, 2017; Kumwimba et al., 2017b; Wu et al., 2013; Zhang et al., 2016a, 2016b). On the other hand, the effectiveness of VDDs in treating polluted water is a complex process that is largely dependent on the reach connections (piped sections and low-grade weirs); biofilms; connectivity between fields and ditches; hydraulic loading; depth; temperature; and ditch network topologies, which in turn can result in variations in removal efficiency of pollutants among different studies (Bouldin et al., 2005; Dollinger et al., 2015; Herzon and Helenius, 2008; Kumwimba et al., 2017c; Lagacherie et al., 2006; Moore et al., 2008; Wu et al., 2014). As the number of influencing factors increases, so does the uncertainty of model experiment predictions. In such situations, Cooman and Schrevens (2006) suggested it is essential to assess the main factors [e.g. assessing factors influencing the most removal rates (Vazquez-Cruz et al., 2014)], and whether or not VDDs can be successful for mitigating pollutants. In VDDs, there are different pollutant removal mechanisms, such as plant uptake, sedimentation, precipitation, volatilization, adsorption, and a variety of microbial processes. These mechanisms are usually directly and/or indirectly impacted by several environmental factors, which can be either internal or external such as the climate condition, temperature, and operation strategies (Kadlec and Wallace, 2009; Vymazal, 2007; Wu and Yang, 2012; Zhang et al., 2016a, 2016b). Despite progress made in the non-point source pollutant removal processes in VDDs over the last few years, there are still gaps in fully understanding these systems.

Most VDDs have been used to treat agricultural runoff, but at present, VDDs have been successfully applied to address other types of wastewaters including animal, domestic sewage, aquaculture, and winery wastewaters (Saunders, 2007; Bundschuh et al., 2016; Kumwimba and Zhu, 2017; Kumwimba et al., 2017b, 2017e). The functional capacity of VDDs in treating primary domestic sewage laden with nutrients, metals and pharmaceutical residues has only been partially assessed to date in most treatment ditches. Currently, several reviews, such as Herzon and Helenius (2008), Needelman et al. (2007), and Skaggs and Schilfgaarde (1999) have been published in international journals and books with regard to either hydrological functioning and engineering in drainage ditches or their biological importance and functioning in biodiversity restoration. Needelman et al. (2007) reviewed the role of drainage ditches related to nutrients, water, and sediment in transfer/transformation. Dollinger et al. (2015) gave a comprehensive and critical review of ditch design and maintenance. Similarly, Faust et al. (2018) summarized different management practices and designs in agricultural ditches and quantified the effects of these management systems on nutrients and sediments losses downstream. The feasibility of VDDs to mitigate these pollutants in agricultural runoff and domestic sewage requires in-depth knowledge on removal efficiencies, mechanisms, the impacts of environmental conditions, and adequate design of ditch characteristics and maintenance. Hence, it is essential to review and discuss recent developments and knowledge on the sustainability of VDD treatment technology.

In this review, we attempt to provide an in-depth analysis of the overall research activities on the application of VDDs for mitigation of non-point source inorganic (e.g., N, P and metals), and organic (e.g., pesticides and pharmaceutical residues) pollutants from domestic sewage and agricultural runoff. Removal efficiencies of these pollutants in VDDs are also summarized in this review in order to assess their performance. Likewise, possible removal mechanisms of these pollutants related to the three essential components of VDDs (bed properties, functional characteristic, and microbes) are also assessed. Finally, the main summary, future research needs, and system design and operation are highlighted. This review will lead to a scientific understanding of the complex interaction between the removal pathways, environmental conditions, and operational parameters for enhancing pollutants removal mechanisms in vegetated drainage ditches.

2. Sources of nutrients and organic pollutants in VDDs

Pollutant inputs, compositions, and concentrations to drainage ditches are closely related to dispersed sources or locations (Edwards and Withers, 2008; Kröger et al., 2008a; Kumwimba et al., 2016a, 2016b; T. Wang et al., 2017a). In addition, ditches are ubiquitous in rural, suburban, factory, and agricultural settings (Buchanan et al., 2013; Kumwimba et al., 2016a, 2017a) and can inevitably receive the discharge of nutrients and other pollutants including sediments, pharmaceuticals and personal care products (PPCPs), metals, steroid hormones, toxicants, and pathogens via drainage flows (Dragon et al., 2016; Kumwimba et al., 2017d, 2017e; Schijven et al., 2015; Toet et al., 2005; Zhang et al., 2015). Major sources include agricultural runoff, animal wastewaters, aquaculture waters, domestic sewage, and urban and highway runoff (Fig. 1) (Further information regarding sources of these pollutants in VDDs can be found in supplementary information). Collectively, the results discussed above suggest that ditches, besides conveying excess water from field, may also act as both sink/source to retain or release pollutants into receiving water bodies. Awareness of probable contributions of these mentioned pollution sources to non-point source inorganic and organic pollutants requires that these ditches be considered for their capacity to mitigate pollutants.

3. Prevention and mitigation measures for non-point source pollutants

The most commonly used mitigation techniques for treating nutrients and organic pollutants can be classified into physical, chemical, and biological/ecological treatment. Physicochemical methods encompass mostly advanced oxidation processes, coagulation/flocculation, flotation, membranes, and others. Historically, these technologies have been applied successfully for water environmental control around the world. However, these advanced treatment technologies and methods are costly and not completely feasible for extensive use in rural regions. Taking into account the low level of economic development, shortage of energy, and lack of environmental technical staff in rural and remote zones in developing countries, it is imperative to explore rural domestic wastewater treatment technologies with high efficiency, low investment, low overhead costs, low maintenance, and low power consumption, all of which are essential to address decentralized wastewater. Depending on the production and development processes of these pollutants, three types of strategies have been suggested to mitigate non-point source pollution in rural regions: (a) source control strategies (e.g. optimization of fertilizer application and prevention of water and soil loss); (b) pollutant retention during the runoff process (e.g., VDDs, edge-of-field, CWs, vegetated filter strips and ponds, construction of low-grade weirs); and (c) treatment and restoration of the polluted water pathway (e.g., man-made floating islands, submerged hydrophyte restoration) (Kumwimba et al., 2017e; Ribaudo et al., 2001; Wu et al., 2011, 2017). However, CWs have some limitations, such as

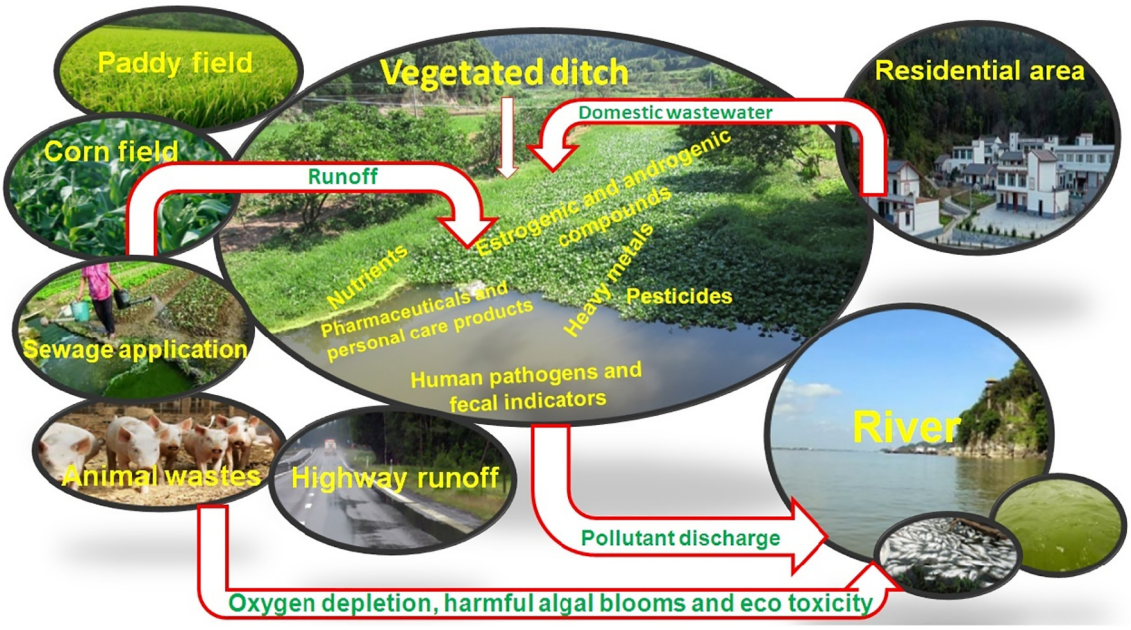

Fig. 1. Primary sources of nutrients and organic pollutants in vegetated drainage ditches.

relatively large space requirements, high retention rates, sediment disposal issues (Tyler et al., 2012), and these large open areas with standing water can be a breeding ground for disease vectors. Although VDDs have not gained as much attention as the other techniques (e.g. CWs), the successful use of VDDs provides a promising extension to domestic sewage technology.

4. The use of VDDs for non-point source pollutant removal in agricultural runoff and domestic sewage

Strategies to minimize adverse environmental effects of farming were particularly prevalent towards the late 1980s and early 1990s in North America and European countries, with the concept of best management practices (BMPs) and agri-environmental schemes (AES), originating from US and Europe, respectively (Dollinger et al., 2015; Dobbs and Pretty, 2001). Agricultural drainage systems are generally seen as conduits for channeling excess water from production acreage (Cooper et al., 2004). Drainage also plays a crucial role in the sustainability and profitability of crop production (Kröger et al., 2008b). Agricultural field drainage activity can be provided by surface or subsurface modifications or even a combination of the two (Madramootoo et al., 2007). Ditches can be found in both developed and developing nations around the world and many researchers have demonstrated the importance of vegetated ditches in regulating downstream nutrient transport to water bodies as well as mitigating organic pollutants (Bouldin et al., 2005; Cooper et al., 2004; Coulson et al., 1990; Ecke, 2009; Nguyen and Sukias, 2002; Rogers and Stringfellow, 2009). During the late 1990s and the early 2000s (e.g. Locke et al., 2011; Moore et al., 2000, 2001a, 2001b, 2002; Kröger et al., 2011), a great series of VDDs were designed in the US (e.g. ARS National Sedimentation Laboratory in Oxford, Mississippi) and Netherlands; efforts were made to assess the mitigation of pesticide and nutrient losses in runoff and their fate. Since these "pioneer" field surveys, many other works on nutrients and organic pollutants (e.g. pesticide) mitigation in VDDs have been conducted (Table 1). At the primary stage, the application of VDDs was mainly tested for treating pesticides following irrigation and storm runoff events. Aiming at cheaper and effective ecological control of non-point source pollution, VDD development has received significant attention for their successful application in mitigating agricultural runoff, storm water, polluted rivers and highway runoff from both local government agencies and scientists over the last several years (Bennett et al., 2005; Needelman et al., 2007; Moore et al., 2008, 2011; Falbo et al., 2013; Ahmed et al., 2015). It has now become a pioneer technique in biological and ecological sewage-fed aquaculture purification. Applications of these systems have also been significantly extended to alleviate environmental pollution by removing a diverse array of pollutants originating from domestic sewage (Saunders, 2007; Moeder et al., 2017; Kumwimba et al., 2016a, 2017e). They have also been developed in various climate conditions such as warm and humid, arid and cold, as well as tropical (Wu et al., 2014). Overall, available case studies have demonstrated promising results for the potential use of VDDs for agricultural runoff and domestic wastewater treatment, depending on conditions and landscape characteristics (Table 1). Despite the potential importance of VDDs in pollutant transport, their role in pollutant reduction strategies has only been partially assessed to date and remains an essential topic of interest.

5. Fate and removal mechanisms of nutrients and organic pollutants in VDDs

Major pollutant removal mechanisms in VDDs are illustrated in Fig. 2. In VDD systems, the transformation and removal of nutrients and organic compounds can occur with the physical, chemical and biological processes, which in turn are largely dependent on several environmental conditions and management practices. The following sections assess the pollutant removal mechanisms and performance of VDD systems treating agricultural runoff and domestic sewage.

5.1. Nitrogen uptake and removal

Mechanisms involved in N removal in VDDs include plant uptake, transformation, sedimentation, volatilization, microbial assimilation, and nitrification/denitrification by bacteria associated with root systems (Kadlec and Wallace, 2009; Kumwimba et al., 2016b; Vymazal, 2007; Wu and Yang, 2012; Zhang et al., 2016a, 2016b). However, loss of NH_4-N through volatilization is insignificant if pH is below 8.0 (Vymazal, 2007). Bacterial nitrification/denitrification is considered as the major avenue for N removal from ditches (Shukla et al., 2011). During the NH_4-N removal process, microbial nitrification/denitrification could result in a permanent removal of N by converting NH_4-N to

Table 1
Removal efficiencies of pollutants in vegetated drainage ditches around the world as reported in the peer-reviewed literature.

	Wastewater type	System	Length (m)	Vegetation	Substrate	Operation parameters	Mean percent removal efficiency (on concentration basis, mg/L)	References
Florida, USA	AD	VDD	nd	*Pontederia cordata*, *Eichhornia crassipes*, *Lemna minor*	Organic sediment and mineral sediment	HRT: 0.11–0.46 days	SRP: 13–55%	Collins et al. (2016)
Mississippi, USA	AD	VDD	389	*md*	21:35:44 (% sand/silt/clay), 0.6% OC	*md*	Permethrin: 44%	Moore et al. (2011)
Mississippi, USA	AD	VDD	402	*md*	21:35:44 (% sand/silt/clay), 0.6% OC	*md*	Chlorpyrifos: 19%	Moore et al. (2011)
Mississippi, USA	AD	VDD UVDD	320	*Typha latifolia*, *Sparganium americanum* and *Juncus effusus*	Soil	HRT: 7 h	TN: 92%, TP: 86%, DIP: 99% TN: 77%, TP: 95%, DIP: 97%	Moore et al. (2010)
California, USA	AD	VDD	200	*Myzus persicae*, *Hypera postica* and *Hypera brunneipennis*	21:35:44 (% sand/silt/clay), 0.6% OC	*md*	Chlorpyrifos: 38%	Gill et al. (2008)
Mississippi, USA	AD	VDD	400 and 460	Hydrophytic emergent and submerged species	Soil	*md*	DIP: 43.9	Kröger et al. (2008a)
Mississippi, USA	AD	VDD	400 and 460	*Leersia oryzoides* L., *Sagittaria latifolia* Willd., *Juncus effusus* L., and *Echinodorus cordifolius* (L.)	Soil	*md*	TN: 57%	Kröger et al. (2007a)
North Carolina, USA	ARCs	VDD	36	*Ludwigia*	A coarse- to medium-grained sand covered by varying accumulations of silt		Nutrient uptake was estimated to remove >46 to 75% of the NH4 load and 13 to 66% of the PO4 32 load during high flow periods.	Ensign et al. (2006)
Mississippi, USA	ARCs	VDD	280	*Ludwigia*, *Lemna*, *Polygonum*		HRT: 7 days	Pyrethroid concentrations reduced to 0.1% of initial concentration within 280 m	Bennett et al. (2005)
Mississippi, USA	AD	VDD	650	*md*	*md*	HRT: 6 h	λ-Cyhalothrin: 98.8%	Bennett et al. (2005)
Mississippi, USA	AD	VDD	650	*md*	*md*	HRT: 6 h	Bifenthrin: 96.1%	Bennett et al. (2005)
Mississippi, USA	ARCs	VDD	600	*Ludwigia*, *Polygonum*, *Leersia*		HRT: 3–6 h	Pyrethroid concentrations decreased to 0.1% of initial concentration within 510 m	Cooper et al. (2004)
Mississippi, USA	AD	VDD	600	*Ludwigia peploides*, *Polygonum amphibium*, and *Leersia oryzoides*	Soil	HRT: 1.5 h	Esfenvalerate: 99%	Cooper et al. (2004)
Mississippi, USA	ARCs	VDD	200	*Polygonum*, *Leersia*, *Lemna*		HRT: 7, 14, and 28 days	Lamba-cyhalothrin and bifenthrin reduced to below ecotoxicological thresholds within VDD	Cooper et al. (2002)
Mississippi, USA	ARCs	VDD	50	*Polygonum*, *Leersia*, and *Sporobolus*	Soil	HRT: 7 days	Atrazine and pyrethroid concentrations were decreased to "no effects" level within 50 m	Moore et al. (2001a, 2001b)
Jiangsu, China	AD	VDD	50	*Lolium perenne* L.	*md*	*md*	TN: 23–62%	Min and Shi (2018)
Sichuan, China	AD	VDD	300	*Alternanthera philoxeroides*, *Phyla nodiflora*, *Oenanthe javanica*, *Polygonum*	Soil	HRT: 0.11 days	TN: 31%, TP: 28%	Kumwimba et al. (2017c)
Sichuan, China	DS	VDD	300	*Cyperus alternifolius*, *Iris pseudacorus*, *Canna indica*, *Thalia dealbata*, *Acorus gramineus*, *Hydrocotyle vulgaris*, *Myriophyllum aquaticum*	Soil	HRT: 0.15 days	TN: 61%, NH_4-N: 63%, NO_3-N: 48%, TP: 58% and PO_4-P: 51%	Kumwimba et al. (2017d)
Sichuan, China	DS	VDD	300	*Cyperus alternifolius*, *Iris pseudacorus*, *Canna indica*, *Thalia dealbata*, *Acorus gramineus*, *Hydrocotyle vulgaris*, *Myriophyllum aquaticum*	Soil	HRT: 0.12 days	Ni: 51, Cu: 56, Cr: 63, Zn: 79, Cd: 68, Pb: 80, As: 60, Fe: 53, Al: 20, Mn: 24	Kumwimba et al. (2017d, c)
Jiangxi, China	AD	VDD	170	*Sagittaria sagittifolia*, *Zizania latifolia*, *Fimbristylis miliacea*, and *Nelumbo nucifera*	*md*	HRT: 3–5 days	TN: 9.3%, TP: 14.0%	Cai et al. (2017)
Tianjin, China	AD	VDD	30	*Zizania aquatica*, *Bermuda grass*	hollow hexagonal bricks, Zeolite	*md*	TN: 24.66%–30.39%	X. Wang et al. (2017b)
Hunan, China	SF	MS	0.5	*Myriophyllum aquaticum*; and *Ipomoea aquatica*, *Zizania latifolia*, and *Nasturtium officinale*	32.6% sand, 41.1% silt, and 26.3% clay.	HRT: 28 days	NH_4-N and TN: >97%	Liu et al. (2016), Zhang et al. (2017)
Hunan, China	DS	WM	1.5	*Myriophyllum aquaticum*,	Soil (sand, silt, and	HRT: 30	TN: 50.9% and 36.3%	Zhang et al. (2016a,

Table 1 (*continued*)

	Wastewater type	System	Length (m)	Vegetation	Substrate	Operation parameters	Mean percent removal efficiency (on concentration basis, mg/L)	References
				Alternanthera philoxeroides	clay contents of 41.3%, 35.3%, and 23.4%)	days		2016b)
Xi'an, China	STPE	VDD	15	*Lolium perenne*	Hydroponic	HRT: 6 days	TP: 27.7%; NH_4-N: 82.8%	Ren et al. (2016)
Tianjin, China	AD	VDD	6	*Iris pseudacorus*, *Lythrum salicaria*	Soil, volcanic rocks, brick fragments	HRT: 3 days	TN: 33.06%	Li et al. (2016)
Hunan, China	AD	VDD	16	*Pontederia cordata* and *Myriophyllum elatinoides*	Soil	*md*	NH_4-N: 50.8–71.4%	Zhang et al. (2016a, 2016b)
Jiangsu, China	AD	VDD	300	*Hydrilla verticillata*, *Zizania latifolia*, *Phragmites australis*, *Nelumbo nucifera*, *Trapa bicornis osbeck*	*md*	HRT: 5–7 days	TN: 87.8%, TP: 70.4%	Xiong et al. (2015)
Hunan, China	AD	VDD	200	*Canna indica*, *Hydrocotyle vulgaris*, *Sparganium stoloniferum*, *Myriophyllum* sp., and *Juncus* sp.	Soil	*md*	TN: 75.8%, NO_3-N: 63.7%, NH_4-N: 77.9%	Chen et al. (2015)
Jiangsu, China	AD	VDD	200	*Soybean*, *Bermuda grass*, and *Perennial ryegrass*	Geogrid, geotextile, fine gravel (size: 4–8 mm) of 0.15 m, and coarse gravel (size: 16–32 mm)	*md*	TN: 57%, TP: 60%, NO_3-N: 6.8%, NH_4-N: 49%	Fu et al. (2014)
Zhejiang, China	AW	VDD	470	*Hydropiper*, *Eichhornia crassipes*, and *Origanum vulgare.*	*md*	HRT: 1 day	TN: 75% and 69%, TP: 82% and 86%	Wu et al. (2014)
Guangdong, China	AD	VDD	100	*Cyperus alternifolius* and *Iris tectorum*	Gravel and sand	*md*	NH_3-N: 15%, COD: 27%, TN: 50%, TP: 63%	He et al. (2012)
Jiangsu, China	DS	VDD	230	*Scirpus tabernaemontani*, *Canna indica*, *Zizania latifolia*, *Juncus minimus*, *Cyperus alternifolius*, *Zantedeschia aethiopica*, and *Acorus calamus*	Soil and ceramiste	*md*	NH_3-N: 58%, NO_3-N: 53%, TN: 52%, TP: 56%, TDP: 48%	Wu et al. (2011)
Jiangsu, China	AD	VDD	30	*Ipomea aquatica*, *Oryza* and *Oenanthe javanica*	Soil	*md*	TN: 54%, TP: 82%	Wang et al. (2010)
Jiangsu, China	DS	VDD	76	*Acorus calamus*, *Zantedeschia aethiopica*, *Arrowhead* and *Oenanthe javanica*	Gravel, ceramistic and bamboo charcoal	*md*	NH_3-N: 67%, NO3-N: 70%, COD: 58%, TN: 48%, TP: 61%, TDP: 78%	Yin et al. (2008)
Beijing, China	AD	VDD	290	*Reed*	*md*		TN: 92%, TP: 65%	Yin et al. (1995)
Utrecht, Netherlands	STPE	VDD	50	*Phragmites australis*, *Typha latifolia*	Soil	HRT: 4 days	TN: 45%	(Toet et al., 2005)
Wageningen, Netherlands	AD	VDD	40	*Myriphyllum*, *Elodea*, *Sagittaria*	Silty clay loam	HRT: up to 7 days	94–98% insecticide added was removed from water column by day 3	Leistra et al. (2004)
Wageningen, Netherlands	A supply reservoir	VDD	40	*Myriophyllum spicatum*	Sandy loam OM = 26%	HRT: 7 days	40–60% of applied linuron was discharged from VDDs	Crum et al. (1998)
Utrecht, Netherlands	Wet meadow	VDD	*md*	*Fontinalis*	*md*	*md*	TP: 90–95%	Meuleman and Beltman (1993)
Koblenz-Landau, Germany	AD	VDD	22–176	*Lemna minor*, *Typha angustifolia*, *Sparganium erectum*, *Phragmites australis*, *Iris pseudacorus*, *Carex elata*, *Glyceria* sp.	Loamy sand	HRT: 1–11 h	Fungicide: 53%	Bundschuh et al. (2016)
Krottenbach, Landau, Gemany	AD	VDD	44	*md*	Loamy sand, OC0: 78%	HRT: 1.3 h	Indoxacarb: 92%, Trifloxystrobin: 97%, Thiacloprid: 97%	Elsaesser et al. (2013)
Krottenbach, Landau, Gemany	AD	VDD	44	*md*	Loamy sand, OC0: 78%	HRT: 1.3 h	Tebuconazole: 92–97%	Elsaesser et al. (2013)
Berlin, Germany	DS	VDD		*Potamogeton*, *Sparganium*, *Phalaris*, *Glyceria*	Fine sands OM = 5.9%	*md*	Uptake rates of PO_4-P, NH_4-N, NO_3-N were high compared to pristine systems but retention was low due to high loads	Gucker and Pusch (2006)
Kiel, Germany	Groundwater-fed	VDD	150	*Phalaris arundinacea*, *Carex acutiformis*	*md*	*md*	NO_3-N: 79%	Scholz and Trepel (2004)
Ferrara, Italy	AD	VDD	1000	*Typha angustifolia*, *Phragmites australis*	Soil	HRT: 1.5–4 h	TN: >50%	Pierobon et al. (2013)
Milan, Italy	Nitrate-rich spring waters	VDD	380	*Typhoides arundinacea*	Soil	*md*	Removal rate of N expressed on an areal basis (38–84 mmol N m^{-2} d^{-1})	Soana et al. (2017)
		UVDD	330				12–45 mmol N m^{-2} d^{-1}	
Melbourne, Australia	AD	VDD	160	*Lolium perenne*, *Trifolium repens*, *Paspalum* spp., *Cyperus* spp.	*md*	*md*	TP: 72.72–87.27%	Barlow et al. (2003)

(*continued on next page*)

Table 1 (*continued*)

	Wastewater type	System	Length (m)	Vegetation	Substrate	Operation parameters	Mean percent removal efficiency (on concentration basis, mg/L)	References
Griffith, Australia	AD	VDD	1100	*Paspalum*, *Typha*, *Potamogeton*, *Schoenoplectus*, *Ludwigia*, *Vallisneria*, *Elodea*, *Sagitaria*	*md*		TN: 75% TP: 100% NO_3-N: 93%	Bowmer et al. (1994)
Sinaloa, Mexico	AD, DS	VDD	3600	*Typha domingensis*	Soil	*md*	Diclofenac: 90%, Ibuprofen: 98%	Moeder et al. (2017)
Prague, Czech Republic	AD	VDD	200	*Phragmites australis*, *Typha latifolia* and *Glyceria maxima*	*md*	*md*	TN: 38%–53%, NO_3-N: 41.4%–62.2%, TP: 52.6% and 51,3%	Vymazal and Březinová (2018)

md: missing data, AD: agricultural drainage, DS: domestic sewage, SF: swine farm, AW: aquaculture wastewater, STPE: sewage treatment plant effluent, ARCs: agricultural row crops.

gaseous nitrous and nitric oxide, and eventually N_2 gas. Performance of the VDDs for treatment of polluted water can be affected by many factors such as ditch plant species, growth stage, retention time, nutrient loading rates, velocity, water conditions, and other environmental conditions. Vymazal and Březinová (2018) found that removal of N was strongly dependent on water temperature. Nutrient content of ditch plants growing in domestic sewage tended to be higher than those in mixture of domestic sewage (Kumwimba et al., 2017a, 2017b, 2017c, 2017d, 2017e, 2017f; Saunders, 2007). Although poorly explored, water velocity is the most variable factor exerting a primary control on VDD nutrient dynamics and denitrification (Castaldelli et al., 2018). Within VDDs, high removal efficiencies of nutrients were observed when discharges were the lowest (e.g., May and June) and HRT the highest (Kumwimba et al., 2017a, 2017b, 2017c, 2017d, 2017e, 2017f; Soana et al., 2017). In VDDs, removal of NO_3 via denitrification in vegetated sediments was strongly influenced by flow conditions (Castaldelli et al., 2018). Generally, at long HRT, VDDs and canals function as linear wetlands, where interactions with the benthos increase biogeochemical reactions, promoting N degradation. Nitrogen uptake and storage by plant species is a key mechanism of N removal from water in aquatic systems. The contribution of ditch plants in terms of nutrient removal has been observed to be high, accounting for 41–86% of the influent TN and TP loads in a field mesocosm study of VDD sediments receiving primary domestic wastewater (Kumwimba et al., 2017f). In 200 m VDD treating agricultural drainage, Vymazal and Březinová (2018) found that plant uptake was responsible for 26% of the removed N. Reddy and Busk (1985) and Silvan et al. (2004) have reported that plant uptake could decrease TN between 16 and 75%. Kumwimba (2017) and Kumwimba et al. (2017b, 2017d) studied the functional capacity of VDDs for the treatment of a mixture of primary domestic sewage and agricultural runoff and found the presence of plant species resulted in high nutrient removal. It was concluded in these studies that plants, physical settlement, substrate, warm environments, and appropriate management practices in VDDs played considerable roles in successful N removal capacities. Li et al. (2016) also demonstrated using a VDD model that TN was decreased by 33% via the influence of substrate adsorption and interception, plant uptake and reaction in the root zone, and microbial degradation. Chen et al. (2015) evaluated the efficiency of VDDs treating agricultural drainage and reported the systems reduced N by 76% in summer. Vegetated ditches with *Eichhornia crassipes* (water hyacinth), *Bacillus subtilis* (the bacterium), and the freshwater snail *Bellamya aeruginosa* were reported to reduce TN by 69 and 75% from wastewater discharged by Chinese soft-shelled turtle greenhouse cultivation according to Wu et al. (2014). Fu et al. (2014) investigated the removal of nutrients in VDDs receiving farmland surface runoff and found removal efficiencies were 57, 6.8 and 49% for TN, NO_3 and NH_4, respectively. Kröger et al. (2007a) analyzed N reduction capacity of farm ditches under natural conditions, in northern Mississippi, and results showed ditches reduced 57% of N over the 2-year study period. Wu et al. (2011) found a mean reduction of 52, 53, and 58% for TN,

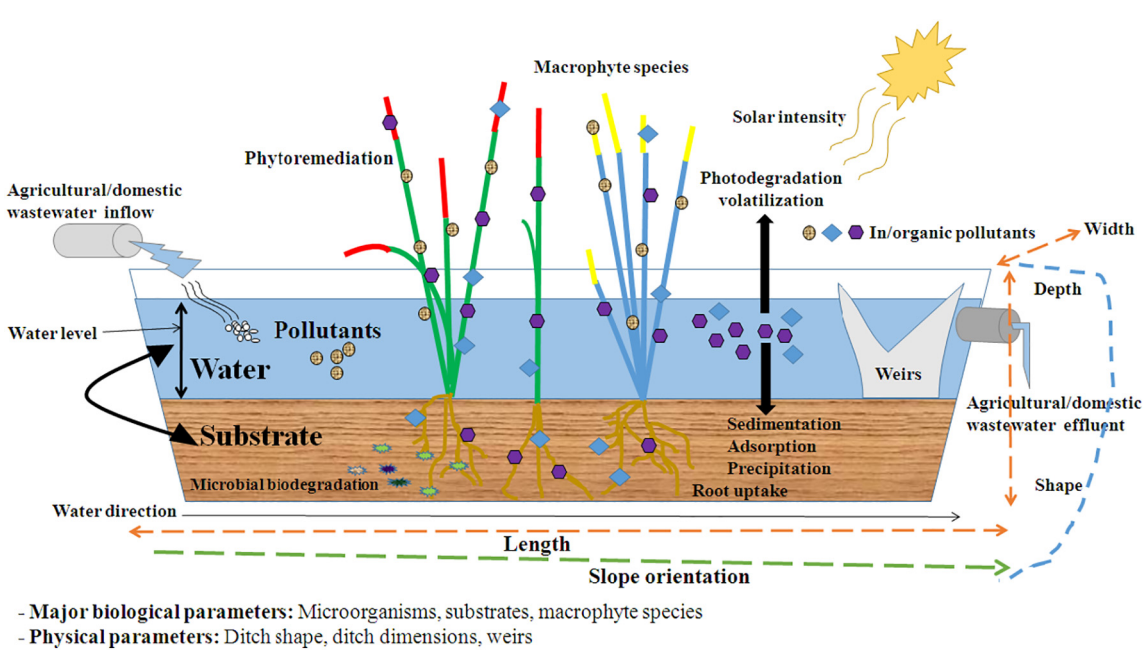

Fig. 2. Major functional characteristics of VDDs for the removal of nutrients and organic pollutants.

NO_3-N, and NH_4-N, respectively, for VDDs. Sufficient contact between plants and water column is essential in mitigation of pollutants (Bouldin et al., 2005).

5.2. Phosphorus uptake and removal

Unlike N, the key mechanisms of P removal in drainage ditches are driven by physical and chemical processes and use of filter materials. Phosphorus sorption reactions in ditch sediments are regarded as important mechanisms for P removal (Needelman et al., 2007; Nguyen and Sukias, 2002). In acidic soil/sediment, P sorption likely involves Al and Fe compounds, whereas in calcareous or alkaline soil/sediment, P sorption is controlled by Ca and Mg compounds (Nguyen and Sukias, 2002; Zhu et al., 2012). Moreover, redox potential (Eh) and pH can influence sorption processes (Nguyen and Sukias, 2002; Smith and Pappas, 2007; Zhu et al., 2012). As a result, ditch sediments might serve as a P sink as water flows through them, only to switch to a P source under certain physicochemical and biological conditions (Smith and Pappas, 2007). Overall, plant uptake and microbial degradation are responsible for phosphate ($PO^{3-}{}_4$) removal, while precipitation and retention capacity within substrates generally represent the most significant removal pathways of all P forms. According to Kröger et al. (2007b), plants usually absorb 5% of nutrient fluxes. Kim and Geary (2001) demonstrated that plant harvesting removed <5% of TP present in vegetated microcosms, while >95% was stored in substrates. This observation was also reported in VDDs treating wastewater by Saunders (2007) who found that the majority of P is associated with benthic sediments rather than being stored in ditch plants. Depending on the pollutant concentrations in the water column, hydrological variables (HRT and HLR), and climatic conditions, ditch plants can incorporate higher amount of these pollutants (Kröger et al., 2007a, 2007b; Collins et al., 2016; Kumwimba et al., 2017a, 2017b, 2017c, 2017d, 2017e, 2017f; Saunders, 2007; Castaldelli et al., 2018). Vymazal and Březinová (2018) reported 51 and 53% removal efficiency of TP in south-central Bohemia, Czech Republic, and plant uptake was responsible for 14% of the removed load. These authors concluded that the removal of P was temperature-independent. Barlow et al. (2003) reported a significant decrease in P concentrations in VDD water in the range of 72 to 82%. Reddy and Busk (1985) and Silvan et al. (2004) have reported that plant uptake could decrease TP between 12 and 73%. Moore et al. (2010) reported that VDD had a significantly lower reduction of TP loads (86%) than unvegetated ditches (95%). A possible reason may be that dense vegetation inhibited phosphorus removal by periphyton and co-precipitation mechanisms (Wen and Recknagel, 2006).

5.3. Accumulation and removal of metals

Sedimentation is the major mechanism removing metals within VDDs. However, there are a number of other processes including filtration, chemical precipitation, adsorption, biological sequestration, microbial interactions, chemical transformation and volatilization that can also play an important role. Sorption to gravel or soil substrates have also been attributed with the removal of metals within VDDs (Kadlec and Knight, 1996; Kumwimba et al., 2017d). Kumwimba et al. (2017d) reported the annual mean removal efficiencies of Ni, Cu, Cr, Zn, Cd, Pb, As, Fe, Al, and Mn in the VDDs receiving domestic sewage to be 51, 56, 63, 79, 68, 80, 60, 53, 20, and 24%, respectively. The same study also reported concentrations of these metals were significantly higher in sediments at the inflow of the VDDs than at the middle and outflow, indicating that metals adsorb to sediments near the inflow. Similar observations were also reported by Lesage et al. (2007a, 2007b), Vymazal (2003), and Vymazal et al. (2010) in CWs treating municipal wastewater. Median removal efficiencies of 43, 85, 78, 9, and 66% for Cr, Cd, Ni, Pb, and Zn, respectively, were observed in a vegetated pond receiving highway runoff (Revitt et al., 2004). Kumwimba et al. (2017e) explored the differences in metal/metalloid accumulation by 10 dominant ditch plant species in a VDD impacted by primary domestic sewage and found concentrations of metals in VDD plants were positively related to that in VDD sediment. They also reported that accumulation of heavy metals varied among species and plant parts, although sequestration by plants represented only a small proportion (<1%) of the inflow load. Vegetated ditches are commonly utilized to mitigate nutrients and pesticides, but information on metal removals remains limited. Accumulation of metals in VDDs treating domestic sewage is not a topic of priority, mainly because the concentrations of metals are typically lower. Moreover, presently there are no discharge standards for metals in VDDs. As a result, metals have been neglected historically in most treatment ditches. Nevertheless, metals in domestic sewage may be associated with fine particulate matter, and the long-term deposition of sewage to VDDs often results in the accumulation of high levels of metals in ditch sediments (Kumwimba et al., 2016a, 2016b, 2017e; Rattan et al., 2002) and ditch plant species. In short, comprehensive studies evaluating heavy metal contamination status in VDDs to provide a reference for the large-scale control and management of metals are imperative.

5.4. Plant uptake and removal of organic pollutants

Many organic pollutants, including pesticides, polycyclic aromatic hydrocarbons (PAHs), artificial sweeteners and pharmaceutical residues are sequestered in plant tissues (e.g., stems, leaves, or roots) either from soil or air, depending on the properties of the compounds (Dordio et al., 2011a). Generally, the roots are the first plant parts exposed to the organic pollutants thus sequestration through roots is the most common form of absorption. After being assimilated into plants, these pollutants could be degraded via metabolism processes (e.g. transformation of parent organic compounds; conjugation of metabolites with macro molecules; or incorporation of conjugated products into plant cell walls and vacuoles) (Dordio and Carvalho, 2013).

It has been demonstrated that the presence of plants in drainage ditches played a positive role in the mitigation of some organic pollutants such as metalaxyl, thiacloprid, chlorpyrifos, esfenvalerate, linuron, pyrethrin, mesotrione, *S*-metolachlor, terbuthylazine, carbofurane, caffeine, carbamazepine, carbamazepine, ibuprofen, diclofenac and naproxen, and PAHs (Bennett et al., 2005; Cooper et al., 2004; Crum et al., 1998; Garcinuño et al., 2006; Kröger et al., 2009; Moeder et al., 2017; Moore et al., 2011; Otto et al., 2016). In VDDs, assimilation and retention efficiency of these compounds by vegetation is a function of physical and chemical properties of individual compounds as well as, water and soil characteristics and vegetative structure and morphology of the ditches (Dordio and Carvalho, 2013; Stottmeister et al., 2003; Vallée et al., 2014). Ditch plants assimilated organic pollutants (pesticides and PAHs) mainly in roots (5–1065 μg kg^{-1} d.w.) and PAHs accumulation were found in the following order: anthracene (mean 92 ng g^{-1} d.w.), fluoranthene (46 ng g^{-1} d.w.), pyrene (36 ng g^{-1} d.w.) and phenanthrene (20 ng g^{-1} d.w.) (Moeder et al., 2017).

Moore et al. (2008) studied the effectiveness of perennial plant species like *Lolium multiflorum* (annual ryegrass) and *Hordeum vulgare* (barley) to decrease pesticides in VDDs. Within ditches, pesticide removal encompasses biological (microbial degradation, uptake by plants and organisms), chemical (volatilization, photolysis and degradation) and physical (sorption) processes. Generally, VDD mitigation is based on ditch vegetation cover and density; attributes and abundance of ditch-bed materials (including sediment, living and dead vegetation, and ash); ditch length, reach connections; and flow velocity (Dollinger et al., 2015, 2016; Margoum et al., 2006; Stehle et al., 2011). Many studies investigated the fate of pyrethroids experimentally introduced into slow-flowing VDDs (Bennett et al., 2005; Moore et al., 2001a). These authors found a >99% reduction of pyrethroid concentrations within a 50-m segment due to 87% sorption to plants. They also indicated in a further investigation a retention of about 55% and 25% of chlorpyrifos by

sediments and plants, respectively, in ditch mesocosms (59–73 m in length). Additionally, they reported a >90% decrease in concentration and in situ toxicity of chlorpyrifos (Moore et al., 2002). Moore et al. (2011) also reported chlorpyrifos and permethrin were reduced by 20% and by 67%, respectively in VDD draining alfalfa and tomato fields. Sorption of pesticides to sediment/soil, and macrophytes could clearly contribute to their reduction in complex ditch habitats (Bennett et al., 2005; Rogers and Stringfellow, 2009). With regards to the mitigation capabilities, an effective VDD length is required. Ditch lengths of 120 m and 280 m were assessed to decrease bifenthrin and lambda cyhalothrin (Bennett et al., 2005). Other researchers reported that VDD length of 40 m to be required to decrease a worst-case runoff-related concentration of the organophosphate insecticide methyl-parathion (Schulz et al., 2003). Additional study is required to assess the efficiency of the systems based on the length. Mitigation of the investigated pesticides in irrigation runoff by VDDs is listed in Table 1.

Other research using ditches to reduce concentrations of the herbicides were successful, with 61% of atrazine and 78% of lambda-cyhalothrin being sequestered in ditch plant parts (Moore et al., 2001a). Otto et al. (2016) evaluated the mitigation of mesotrione, *S*-metolachlor and terbuthylazine in a vegetated ditch after an extreme runoff event. These findings indicated the distance required to reduce initial concentration by 50% was about 250 m. Generally, at the ditch outlets, concentrations were lowest, and the mitigation was 99%, 91% and 97% for mesotrione, *S*-metolachlor and terbuthylazine, respectively, in 100 m of vegetated ditch for moderate runoffs of low intensity. Carvalho et al. (2012) also reported the ability of macrophytes like *Phragmites australis* to assimilate veterinary pharmaceuticals from aquatic media. Generally, VDDs treating domestic sewage reduced DDE, acesulfame, naproxen, ibuprofen, diclofenac and PAHs by 35%, 5.91%, 90%, 96%, 90% and 81% respectively (Moeder et al., 2017).

In summary, the ability to mitigate non-point source inorganic and organic pollutants appears to be another valuable ecological benefit of VDDs besides their primary functions to collect surface/subsurface water, drain excess water and prevent soil erosion. Plant species which possess many proprieties associated with the treatment process may play a key role in VDDs and are important components of the VDD design. Only few species however, have been utilized to treat agricultural runoff and domestic sewage laden with high concentrations of nutrient and organic pollutants in both summer and winter. Screening and identification of ditch plant species with potential for high biomass production and pollutant removal should be a focus of future studies.

5.5. Microbial communities

Because of their bioconcentrating and metabolic attributes in biological mitigation processes (i.e. pollutant degradation, accumulation, and removal), the use of microorganisms is becoming more widespread in surface water and domestic wastewater treatment. Microorganisms are a diverse and highly abundant component in ditch soils/sediments (Baker et al., 2015). Activities of microbial communities implicated in biogeochemical cycles of VDD sediments are essential for the functions of ditches, because they play an important role in nutrient and organic chemical transformation mechanisms (Baker et al., 2015; Scholz and Lee, 2005). An in-depth knowledge of microbial communities and activities within vegetated treatment systems, including VDDs, is required to give a better understanding of how to enhance design and advance management strategies in VDD to minimize pollutant loading to surface water bodies. Pollutant removal and microbial activity in VDDs are closely tied to the cycling of pollutants. Plants can stimulate denitrification (Taylor et al., 2015). For instance, plants could provide substrate and surface for epiphytic bacteria growth, and have significant connection with microbial functional diversity, biomass and activity; they also provide degradable organic matter for denitrification process. Furthermore, microgradients in redox potential located in plant beds can enhance coupled nitrification-denitrification process. Putting all these mechanisms together tends to lead to a greater removal efficiency of nutrients and organic compounds in vegetated ditches than unvegetated ditches. During nitrification, ammonium (NH_4) or ammonia (NH_3) is converted into nitrite (NO_2-N) and then nitrate (NO_3-N) by ammonia-oxidizing bacteria. Ammonia oxidation, the first and rate-limiting step of nitrification processes in a wide range of systems, performed by two major microbial groups under aerobic conditions [ammonia-oxidizing bacteria (AOB) and archaea (AOA) through ammonia monooxygenase (AMO) as the key enzyme], and thus, important to pollutants biodegradation and the global nitrogen biogeochemical cycle.

Denitrification is the main pathway removing N in aquatic environments (Kreiling et al., 2011; Seitzinger et al., 2006), in which nitrate (NO_3-N), the dominant form of inorganic (N) is converted to gaseous forms of N [mainly nitric oxide (NO), and some nitrous oxide (N_2O)], and eventually transformed to N_2 gas, in the absence of oxygen (Seitzinger, 1988; Veraart et al., 2017). Denitrification is a type of anaerobic microbial process driven by denitrifiers, and involves nitrate reductase, nitrite reductase, nitric oxide reductase, and nitrous oxide reductase. In addition to temperature and microbial community structure, three environmental parameters typically determine the occurrence and magnitude of denitrification, namely, anaerobic environments (e.g. low oxygen concentration), degradable organic carbon, and large supply of NO_3 (Kröger et al., 2014; She et al., 2017). Such conditions take place in the anaerobic layer of sediments, but also in biofilms on plants and other substrates (Eriksson and Weisner, 1997). Denitrification is an interesting pathway to target, particularly when dealing with cultivated landscapes and their influences on downstream water bodies and pollutant delivery to rivers (Kröger et al., 2014). Many researchers have reported that microorganisms in VDDs, such as nitrifying archaea, denitrifying fungi, aerobic denitrifying bacterial, and heterotrophic nitrifying bacteria (Veraart et al., 2017), play a significant role in the transformation and mineralization processes of nutrients and various organic pollutants (Baker et al., 2015). Until recently, heterotrophic denitrification was considered as the only pathway available to return fixed N from ecosystems to N_2 in the atmosphere. The discovery of anaerobic oxidation of NH_4 (anammox) in different aquatic environments changed this view (Thamdrup and Dalsgaard, 2002). Recent studies have detected the presence and activity of anammox bacterial genus in VDD sediments, including *Candidatus brocadia*, *C. kuenenia*, and *C. anammoxoglobus* (Shen et al., 2016). Their results also demonstrated that this process contributed 2–19% to VDD sediment N_2 production, suggesting this process is an integral N loss pathway in VDDs. Future works studying the anammox bacterial activity in relation to the environment factors (e.g. water temperature, pH and substrate concentrations) that govern anammox activity in VDDs is particularly critical as many VDD sediments are always saturated with water, which create favorable conditions for anammox bacteria in the sediment to occur (Kröger et al., 2014; Moore et al., 2017). High NO_3 concentrations, appropriate redox conditions and tight land-aquatic coupling also make VDDs potential anammox/denitrification hotspots. Furthermore, biodegradation of organic compounds by microbes in ditches can occur under both aerobic and the anaerobic conditions involving the activities of various microorganisms such as heterotrophic bacteria, autotrophic bacteria, fungi (basidiomycetes and yeasts), and specific protozoa (Kadlec and Wallace, 2009). In summary, there is lack of knowledge on the microbial community structure and diversity in VDD systems. Therefore, identification and cultivation of microorganisms and the genes involved in biodegradation and nitrification/denitrification and more specific studies are needed in future.

6. Factors influencing the removal of nutrients and organic pollutants

Overall, ditch water/wastewater quality is influenced by several factors including but not limited to, type of vegetation, low-grade weirs,

type of substrates, maintenance, and seasonal fluctuation, (Kumwimba, 2017; Kumwimba et al., 2017b, 2017c; Sharpley et al., 2007; Smith and Pappas, 2007; Strock et al., 2007). Out of these, low-grade weirs, type of vegetation and sometimes substrate are generally controlled through ditch design. The following sections discuss these influencing factors.

6.1. Low-grade weirs

Scientists as well as land managers are now examining low grade weirs, a controlled drainage strategy in open drainage ditches, to increase removal of pollutants within ditch systems. Low-grade weirs are low, check-dam structures designed to be placed within drainage ditches at different points, based on the slope and length of the given ditch channel (Kröger et al., 2008a). Recent studies have highlighted benefits of using weirs in ditch systems for matters related to increases in hydraulic residence time, decreases in flow velocities at multiple locations, and potential decreases in pollutant concentrations and sediment loads (Kröger et al., 2008b, 2011, 2012). Baker et al. (2016) previously reported that weirs possess the potential to effectively slow water allowing for retention of sediment and nutrients. Kröger et al. (2013) also documented that sediment and P were effectively retained behind weirs. Likewise, weirs have demonstrated to enhance inundation, providing additional suitable habitat conditions for denitrifying bacteria and subsequently provide better conditions for pollution dissipation in ditch systems (Baker et al., 2015). Toet et al. (2005) evaluated the effect of four HRTs, (0.3, 0.8, 2.3, and 9.3 d) on pollutant removal in a VDD system. Their results showed high removal efficiency of N can be accomplished in ditches by increasing HRT (e.g., 4 d). Usborne et al. (2013) investigated eight low-grade weirs for sediment and P accumulation and determined weirs had significantly higher sediment accumulation when compared to reference ditches. Additional works have observed a higher performance of weirs to significantly decrease outlet concentrations and loads of nutrients. Kröger et al. (2011) found significant decreases (79%) in nitrate (NO_3^-) concentration between ditch inlet and outlet with weirs. A study on ditches with weirs from Littlejohn et al. (2014) indicate similar influences on HRT and nutrient reductions of N and P ranging from 14 to 67% in a field-scale investigation. Weirs in drainage ditches maintain soil in a more saturated state, creating anaerobic conditions that optimize biogeochemical processes such as denitrification, ammonia volatilization, and plant accumulation. Kröger et al. (2014) reported that weirs provide improved HRTs and promote better conditions for N dissipation in ditches via denitrification (e.g., 2215 μg of N/m^2/h). On the contrary, Baker et al. (2016) observed both systems with and without weirs, demonstrate the capability of reducing nutrients which is assumed to be caused by hydrological variability (i.e., ditches with and without weirs presented the same flow patterns and with similar mean HRT), but indicated more research is needed to confirm this conclusion by giving attention to precipitation events and the ratio of watershed to drainage ditch area. What then is the appropriate height for weirs? The answer to this question could affect the removal efficiency during pulse events such as storms. Taken together, these results suggest the use of low-grade weirs in VDDs should be considered a viable BMP aiming to mitigate pollutants; moreover, further study of N dynamics is needed to ensure their efficacy or limitation.

6.2. Plant species

Nutrients in ditch water and soils promote both plant growth and biomass production. Plants have been documented to be one of the most effective management practices to decrease the transport of pollutants in agricultural drainage as they provide essential biological functions and supply ecosystems benefits in aquatic environments (Kröger et al., 2009; Bundschuh et al., 2016; Saunders, 2007; Kumwimba et al., 2017b). As one of the most conspicuous features of ditches, plants play another role important in pollutant removal because they may assimilate pollutants from water and sediment/soil, and supply surface area for periphyton and bacteria which cause various biological processes to occur in the rhizosphere. Vegetation in ditches also decreases water velocity, increases HRT, as well as indirectly impacts or creates conditions suitable for pollutant removal (Deaver et al., 2005; Kumwimba et al., 2017b; Kröger et al., 2008a, 2009; Lai et al., 2011; Li et al., 2016; Silvan et al., 2004; Schulz et al., 2003; Vallée et al., 2014; Vaughan et al., 2008; Zhang et al., 2008). Plants within ditches may also facilitate the sedimentation of suspended particles, decrease sediment re-suspension and turbidity, and as a result serve to sequester pollutants. In addition, organic detritus from decaying plant residues promotes the accumulation and supply of organic matter in ditches, thus stabilizing sediment (Needelman et al., 2007). Studies have also reported that plants impact denitrification rates directly and indirectly (de Klein, 2008; Kröger et al., 2014). Plants within ditches have many properties in relation to the treatment of polluted water process that make them an indispensable component of the design. For example, plants can remove nutrients and other pollutants by direct uptake and sequestration into biomass or retention (Bouldin et al., 2005; Hoagland et al., 2001; Kumwimba et al., 2017f; Moeder et al., 2017; Moore and Kröger, 2010a, 2010b; Moore et al., 2013; Tyler et al., 2012). Pollutants accumulated by vegetation can be purified through the harvest of aboveground biomass (Vymazal, 2007). Liu et al. (2013) investigated the impact of VDDs on the P adsorption capacity of ditch soils. Their results indicated that plants in VDDs have the potential to increase P retention in the VDD soils. As a result, any change of plant composition is likely to drive modifications within the microbial community and subsequently affect the removal of nutrients from the system. When compared to unvegetated ditches, vegetated ditches are more efficient at removing pollutants (Zhang et al., 2016a, 2016b; Kumwimba et al., 2017b, 2017f). Within VDDs, Moeder et al. (2017) found that ditch vegetation (*Typha domingensis*) contributed to natural attenuation of the 38 selected organic chemicals (pesticides, PAHs, artificial sweeteners and pharmaceutical residues). Several other smaller-scale mesocosm investigations have observed the abilities of plants to remove some pharmaceuticals such as diclofenac, ibuprofen, ketoprofen, naproxen, salicylic acid, amoxicillin, ampicillin, erythromycin, sulfadiazine, sulfamethazine, sulfamethoxazole, atenolol, clofibric acid, carbamazepine and caffeine (Dordio et al., 2009, 2010, 2011b; D.Q. Zhang et al., 2012, 2013a; J. Zhang et al., 2013b). Generally, the uptake and translocation of organic chemicals within plants can be simply driven by diffusion (Dordio and Carvalho, 2013; Li et al., 2017). In mesocosm experiments designed to mimic ditch treatment processes, species such as *Leersia oryzoides*, *Typha latifolia*, *Saururus cernuus*, *Myriophyllum spicatum*, and *Echinodorus cordifolius* were found to be more efficient at mitigating nutrients (Tyler et al., 2012, Moore and Kröger, 2010a, 2010b). Kumwimba et al. (2017f) exposed 18 plant species found in ditches to domestic sewage (e.g., TN: 59 mg/L and TP: 5 mg/L) and showed that *Acorus calamus*, *Canna indica*, *C. generalis*, *Cyperus alternifolius*, *Colocasia gigantea*, *Eichhornia crassipes*, *Iris sibirica*, and *Typha latifolia* had the highest efficiencies for N and P removal. Kumwimba et al. (2017a, 2017b, 2017c, 2017d, 2017e, 2017f) and Moore et al. (2013) found seasonal variation in nutrient mitigation for plant species between summer and winter. These authors concluded that no single species was most effective in eliminating nutrients and removal efficiencies were different depending on the season. Given the various ways plants can improve the removal of pollutants from the water column; it is possible that some species are more effective at mitigation than others (Tyler et al., 2012). As a result, maintaining a variety of different species (e.g., polycultures than monocultures) in VDDs with complementary pollutant removal capabilities may be required to effectively reduce these pollutants sustainably throughout the year (Bouldin et al., 2005, Tyler et al., 2012). Macrophytes found in drainage ditches can be classified into four groups: Emergent plants, floating leaved rooted plants, submerged plants and free-floating plants. Table S1 displays the most commonly used plants in VDDs for the

treatment of polluted waters. In summary, flow velocities in ditches are often low except during pulse events (e.g., storms). These characteristics, often in conjunction with high nutrient concentrations in both ditch water and soils, promote plant growth and biomass production. Consequently, understanding how plants impact the fate and transport of these pollutants is particularly relevant for the performance of VDD systems.

6.3. Plant harvesting

Nutrients and other pollutants assimilated by ditch plants have been reported. In VDDs, aquatic plants grow and emerge during spring and summer, but at the beginning of autumn, plants begin to decay and decompose during the rest of the year, In their study, Kumwimba et al. (2017c) found plant harvesting can also enhance pollutant removal efficiencies in VDDs, as the purification stage is followed by the decay stage. Reddy et al. (1999) reported that aboveground plant tissues releases N and P to the water column, while belowground plant tissues release N and P to the sediment. Kröger et al. (2007a, 2007b) demonstrated that wetland plants are capable of retaining nutrients in high concentrations, but decomposition of vegetation may lead to the release of the retained nutrients, thus, becoming a source of nutrients to the water column. Nahlik and Mitsch (2006) explained that harvested plants are often deposited adjacent to the wetlands, thereby allowing nutrients to return to the wetland upon decomposition. The benefit of plant harvesting for the removal of nutrients or plant growth and productivity and nutrient cycling in treatment systems has been reported. Annual (Kadlec and Wallace, 2009; Toet et al., 2005) and multiple harvestings of plant biomass (Jinadasa et al., 2008; Vymazal et al., 2010) strategies have been proposed as a good option for a system's management and performance. Regular harvesting of the shoots can stimulate new growth of plants and thus enhance plant uptake and storage capacity for N and P, consequently enhancing water purification and improving flow efficiency within systems (Kuehn and Suberkropp, 1998). Harvested biomass can be utilized directly as animal or human food sources, green compost material, energy (via bioenergy plants) and biofuels. Luo et al. (2017) have proposed *Myriophyllum aquaticum* for processing into animal feed and organic fertilizer. Making better use of harvested biomass as valuable by-products can supply important economic advantages to offset the labor costs. Zhao et al. (2012) analyzed chemical composition of plant parts for heavy metals, and found that, according to the National Research Council (NRC, 2000) and China Feed Database (2009) standards (GB 13078-2001), harvested biomass can be utilized to feed livestock. However, standards are different depending on national guidelines; such an approach can result in metal accumulation. Such proposed utilization of biomass requires further research to assess the impacts of long-term consumption of elevated state nutrients and metals. Taken together, the results suggest that an appropriate biomass harvest practice is critical to reach sustainable performance, as the harvesting strategy could increase plant growth and prevent release of pollutants back into water column. In addition, plant recycling may be advantageous in the successful recovery of these pollutants.

6.4. Seasonal fluctuation

Another major concern is the uncertainty surrounding the performance of VDDs under cold climatic conditions and the influence of temperature on biologically/microbiologically mediated treatment processes. With respect to seasonal fluctuation, many research studies have clearly found higher efficiencies of nutrients (N and P) removal in VDDs during warm seasons (Chen et al., 2015; Fu et al., 2014; Kumwimba, 2017; Kumwimba et al., 2017c); however, their performance in low temperatures is still questionable. Typically, as water temperature increase, biochemical processes occur at higher rates in aquatic ecosystems, which could further result in a rapid cycling of nutrients, carbon and oxygen in ditch water column and sediment. Chen et al. (2015) analyzed water quality data for a 200 m long VDDs treating agricultural drainage and found that the removal rates in warms months (April–August) were 2–4 times higher than in cooler months (September–March). Similarly, Kumwimba (2017) and Kumwimba et al. (2017c) observed higher nutrient removal efficiencies in summer and spring rather than winter. Temperature variation considerably impacts the growth and reproduction of microbes. In low temperatures, the metabolism and activity of nitrifying and denitrifying bacteria tend to reduce, which in turn influences the denitrification processes (de Klein, 2008). In the Wageningen test ditch systems, de Klein (2008) reported the effects of temperature were not restricted to the denitrification process itself, as it also involved other processes supporting N removal. Veraart et al. (2011) assessed effects of warming on denitrification rates using microcosm experiments, field measurements and a simple model approach. Their results demonstrated denitrification in aquatic ecosystems is strongly temperature dependent, and that observed effects of temperature on denitrification could be explained by correlated temperature effects on dissolved oxygen. Luo et al. (2005) found that the removal efficiency for N is inhibited when temperatures drop below 10 °C, especially below 6 °C and denitrification is almost stopped under 4 °C (Cookson et al., 2002). Nivala et al. (2007) reported that cold temperatures could impact the metabolism of macrophytes, which provokes a lack of oxygen in the rhizome and subsequently depresses microbial activities. Generally, N removal was largely dependent on microbial activity in root zones and has been demonstrated to be temperature sensitive. In pure cultures, Vymazal (2005) found that the optimum temperature for nitrification ranged from 25 to 35 °C. Other studies reported that ammonia volatilization increased 1.3–3.5 times with each 10 °C rise in temperature from 0 to 30 °C, and denitrification rates almost doubled (1.5–2.0 with each 10 °C increment) (Ng and Gunaratne, 2011). In summary, successful VDD treatment system likely will occur in warm areas, as low temperature conditions may negatively influence treatment effectiveness. The possibility of enhancing the performance of treatment VDDs and future development on the use of VDDs in low temperatures are needed.

6.5. Hydraulic retention time

Hydrology is one of the key parameters governing VDD functions, and flow velocities can also be regulated to reach an adequate treatment performance (Toet et al., 2005). The HRT refers to the average time during which chemicals are in contact with substrates (e.g., soil/sediment) and rhizosphere, which means that HRT could be enhanced by reducing HLR or even enhancing water depth. For removal of these pollutants to occur, a longer HRT must be maintained in a VDD. As mentioned above, plants within VDDs can provide a variety of biological functions and alter the hydrology. Stands of emergent and submerged vegetation generate ditch roughness, drag, and friction, and provide structural complexity that serve to attenuate flow velocity and increase chemical residence time (Kröger et al., 2009). Flow resistance by transport through and around vegetation results in flow becoming usually deeper and slower compared to unvegetated ditches (Soana et al., 2017; Kröger et al., 2009; Liu et al., 2012; Rhoads and Massey, 2012; Zhao et al., 2017). Liu et al. (2012) suggested the ratio between ditch length and width should be enough to improve the hydraulic efficiency. Typically, longer HRT allows for more interaction between chemicals and farmland drainage, whereas at a high hydraulic loading rate (HLR/low HRT), polluted water moves quickly to the outflow, decreasing the contact time among polluted water, rhizosphere, and organisms (Bouldin et al., 2005). In VDDs, a better removal efficiency could reach 90% for aqueous-phase insecticides and 60% for herbicides with a velocity < 0.3 m/s. However, when velocity is about 1 m/s, pesticide attenuation is strongly limited (Dabrowski et al., 2005; Gregoire et al., 2009). In a 152 m stream mesocosm treating wastewater in central California, USA, Craggs et al. (1996) reported that by decreasing the HLR from

1.36 m d^{-1} to 0.44 m d^{-1}, the nutrient removal capacity was improved, which resulted in lower P levels in the outlet. Besides HLR and slope, the HRT is dependent on both the length and width of the system as well as the water depth. Other researchers found a clear correlation between the nutrient loading rate and the nutrient removal rate (Mulbry et al., 2008; Castaldelli et al., 2018). A study reported that there was a non-linear correlation between flow rate and N removal rates (Kangas and Mulbry, 2014). Li et al. (2016) reported that plants and the weirs within VDDs also slowed water flow and extended HRT, which could strengthen N removal. In replicate VDDs, Toet et al. (2005) assessed the impact of four HRTs (e.g., 0.3, 0.8, 2.3, and 9.3 d) on pollutants removal, and demonstrated favorable N removal with a HRT of 9.3 d when compared with other HRTs. These authors further stated that annual P removal was not enhanced by increasing the HRT in VDDs even up to 9.3 d because of the high P mass loading rate. In simulated microcosm systems, Hunter et al. (2001) reported that NH_4-N and PO_4-P removal were considerably higher with a 6 d HRT (80% and 55%) than a 2 d HRT (53% and 29%). Similarly, Shin et al. (2004) found that NH_4-N, NO_3-N, and PO_4-P removal by plants was greater at longer HRTs. Lu et al. (2018) investigated the effects of HRT (e.g., 10 d, 20 d, and 30 d) in water tanks to mimic natural conditions of ponds with plants. These authors indicated that nutrient (TN, NH_4-N, NO_3-N, TP) removal by all three plant ponds could be improved with greater HRT (30 d). In VDD, a low HRT can be linked with incomplete denitrification, and many authors have found that N removal necessitates a longer HRT compared with that needed for decrease turbidity and fecal coliforms (Toet et al., 2005). In their experiments, Li et al. (2016) found that N removal efficiency in VDDs could be impacted by four factors (e.g., influent N concentration > water level > water flow> and suspended solid concentration). Taken together, all the direct evidences suggest that removal efficiency of these pollutants in VDDs is also dependent on the key hydrologic variables, including HLR, HRT, and water depth. Both HLR and HRT have been connected to considerable changes of downstream water quality. Hence, hydrologic variables should be taken into consideration as a critical parameter for management and achieving sustainable treatment performance.

6.6. Selection of substrate material for periphytic biofilms establishment in VDDs

This review has demonstrated that VDDs can be used to mitigate pollutants. However, their performance to decrease these pollutants could be also improved by using suitable substrates (e.g., pumice, coconut fiber, perlite, coarse soil, bamboo, charcoal, peat, sand, and compost). In ditches, the types of substrates might also dictate the establishment of periphyton assemblages and the microbial community structure. A porous media, such as expanded clay, provides a large surface area for wastewater treatment and development of periphytic biofilms. Substrates play a key role in the overall retention of pollutants in drainage ditches (Collins et al., 2016; Fu et al., 2014; Kumwimba et al., 2017c; Li et al., 2016; Liu et al., 2015; Sakadevan and Bavor, 1998; Simon, 2003). Sediments represent a major long-term P sink in ditches, accounting for over 50% of the total standing stock, compared to the other components, such as plants, detritus and water column (Sakadevan and Bavor, 1998; Simon, 2003). Collins et al. (2016), found the capacity of ditches to retain or release P and N differed significantly with sediment characteristics. Their results also demonstrated P uptake was higher in a ditch with organic sediment compared to a ditch with a mineral substrate. Major P removal processes in drainage ditches are achieved largely by adsorption. Furthermore, substrates provide surfaces to allow direct sorption of metal ions. The use of alternative substrates to enhance the retention of pollutants have been proposed by earlier studies but not widely investigated. Fu et al. (2014) reported that the performance of VDDs treating primary sewage can be significantly improved by optimizing the substrates (i.e., system of gravel and geogrid) which optimizes microbial community growth by providing a stable environment. Ullah and Faulkner (2006) investigated microbial denitrification potential of both drainage ditches and constructed wetlands. Results from this study found statistically higher denitrification potentials for fine textured soils as compared to typical silt-loam agricultural soils. It was noted, however, that soil temperature in these systems significantly affects microbial activity, which in turn affects denitrification activity. Roley et al. (2012) noted that freshly excavated soil may be limited in microbial activity due to the change in substrate. Previous research by Groffman (1994) and Groffman and Tiedje (1989) demonstrated finer textured soils resulted in higher organic matter content and thus greater microbial denitrification rates. The amount of microbial biomass is relational to denitrification rates and turnover of N (Groffman and Tiedje, 1989). Inwood et al. (2007) documented denitrification reduced with increasing substrate size due to greater surface area per volume of substratum for microbial colonization on smaller substrata. In their experiment, Li et al. (2016) found volcanic rocks and brick fragments in the VDD had a large surface area, high porosity, and showed an ability to remove N. T. Wang et al. (2017a), and X. Wang (2017b) investigated N removal using a combined VDD with zeolite, and high N removal efficiency was reported suggesting zeolite was a good substrate for microorganism growth. Another study investigated two substrates (rice straw, plastic filling and no substrate) and reported higher TN removal as well as higher abundance of the nitrifying and denitrifying bacteria in the treatment with rice straw as substrate than the other two treatments (Cao and Zhang, 2014). In summary, substrate may offer a suitable growing medium for ditch species and also allow successful transport of water. In addition, substrate sorption could play a significant role in absorbing these pollutants. More research is needed on the efficiencies of different ditch media and their roles in pollutant removal.

6.7. Two-stage ditches

A two-stage ditch (Fig. S2) is a management practice that has been recognized in recent years as an alternative to traditional trapezoidal drainage ditch design to keep flow capacity and stability. It has been modified by adding adjacent floodplains or benches that are inundated by surface flow during storms, thus pipes entering into the ditch to drain in the floodplain, slowing water velocities, and reducing erosion potential. These characteristics of two-stage ditches can be a good tool to reduce pollutants. Earlier studies have found that two-stage ditches provide the potential to decrease sediment load and promote longer residence times between water, floodplain plant and soil allowing higher assimilation of pollutants by the plant and enhancing the denitrification rates (Davis et al., 2015; Hodaj et al., 2017; Roley et al., 2012). Some authors found denitrification rates were enhanced considerable in the benches of the two-stage ditch compared with the side-slopes of the traditional ditch (Powell and Bouchard, 2010). Roley et al. (2012) reported that the assimilation of organic matter on the benches of the two-stage ditch improved the denitrification rates. However, their performance on some mechanisms such as denitrification and plant uptake may be dependent on specific dimensions of the two-stage ditches (e.g., floodplain area, width and depth of the main channel) (Davis et al., 2015; Hodaj et al., 2017). In summary, more in-depth knowledge is required on pollutant concentrations and loads linked with two-stage ditches, as management practice.

6.8. Maintenance for VDDs

Drainage ditches are the final line for defence before pollutants reach larger water bodies such as rivers and lakes. Therefore, management strategies of ditch water and sediments are extremely important for controlling the risk of pollutants entering aquatic ecosystems. This review showed that ditches have a potential risk of releasing pollutants into the water column and sediments. In relation to downstream water-quality, ditch sediment accumulation for extended periods must be minimized, for example by periodically removing sediment,

i.e. dredging, as part of a remediation program. Sediments are considered sinks rather than sources for most pollutants in disturbed environments. It has been reported that metals are immobile in bottom sediments as long as the sediment remains undisturbed (Wasserman et al., 2013). Many studies have reported management strategies in ditches aimed at frequently clearing plants and removing sediment (Dollinger et al., 2017; Kröger et al., 2009; Levavasseur et al., 2014; Needelman et al., 2007; Twisk et al., 2003). Other studies have proposed dredging technologies to remove pollutants from polluted soils (Bortone et al., 2004; Wilhelmsson and Fly, 2012). However, ditch dredging has shown to be potentially harmful to the environment (Fathollahzadeh et al., 2015; Licursi and Gomez, 2009; Nguyen and Sukias, 2002; Prat et al., 1999; Shigaki et al., 2008; Smith et al., 2006). Generally, management practices within a drainage ditch are ultimately a key factor that influence ditch characteristics including plant species and cover, substrate types, and hydraulic structures (e.g., weirs), which consequently directly/or indirectly influence a variety of pollutant removal processes as well as ditch ecosystem functioning (Dollinger et al., 2015). Most common management practices encompass dredging, mowing, chemical weeding and burning using manual techniques (Dollinger et al., 2015, 2017). The direct impact of these operations on the functional and structural characteristics of drainage ditches can be considerable (Table S2) (Smith and Huang, 2010; Smith and Pappas, 2007; Dollinger et al., 2015; Sharpley et al., 2007; Needelman et al., 2007; Kröger et al., 2009): (1) removal of vegetation or alterations of plant species composition through dredging can change or remove the biota sheltered within the ditch responsible for pollutant assimilation; (2) properties of bed material in drainage ditches can be modified after dredging and burning, thus changing the hydrology of the ditch with increased flow velocities and reduced residence times; and (3) greater quantities of pollutants delivered downstream through dredging can have negative environmental and water quality impacts. These impacts can be minimized, for example, by restricting dredging operations to times when pollutant loads are expected to be high, thereby minimizing potential impacts on water quality. Palermo et al. (2008) have introduced a very useful concept-sediment management units (SMU) - for dredging procedures. This constitute a pilot scale portion but representative of the whole dredging area where dredging equipment and the different dredging procedures can be tested and evaluated before embarking on the overall dredging process. These SMU could be used as a function of the physical characteristics of the overall sediments, depth to be dredged, current or wave regimes, concentrations of different pollutants. Moore et al. (2017) investigated the influence of dredging on nutrient concentrations and ecoenzymatic activity in two ditch sediments in the lower Mississippi River Valley. Their results suggested that before undertaking any significant dredging activities, adverse environmental impacts such as nutrient release, loss of buffering capacity, and decreased microbial activity should be weighed against the intended benefits of improved water flow. Iseyemi et al. (2016) investigated the effect of routine mowing of VDDs on pollutant mitigation and examined their transformation along ditch length. Their results demonstrated no significant difference in the mitigation capacities between two treatments (e.g., mowed and unmowed ditches). They concluded that occasional ditch mowing as a management practice would not undermine N and P mitigation capacity of VDDs.

Taken together, all the results discussed above suggest that ditch maintenance could be an efficient practice to maximize ditch services since a number of VDD characteristics vary considerably with ditch maintenance. However, assessing an appropriate approach for the maintenance of the VDDs for enhancing a variety of ditch benefits (Fig. S1) remains the most challenging mission.

7. Incorporation of electron donor carbon for anaerobic removal of pollutant

Generally, an external electron donor is incorporated in water purification systems to improve potential denitrification rates and thus N removal. The selection of an electron donor is crucial for both suitable denitrification rates and long-term effective treatment performance in VDDs. Many electron donors have been utilized to purify various types of wastewater (Burchell et al., 2007; Faust et al., 2016; Greenan et al., 2006; Ingersoll and Baker, 1998; Liu et al., 2015). In ditch systems, the routes that contribute to N removal mainly include microbial nitrification-denitrification and plant uptake, which is considered to be the prevailing and long-term long-term mechanism for N removal. The use of low-grade weirs in VDDs increases nutrient removal by creating anaerobic conditions favorable for denitrification, in which an electron donor (e.g., organic carbon) is required. Denitrification rates of microbial communities in turn may be affected by many factors, including temperature, nitrate concentration and especially the organic carbon source. Carbon sources in a VDD system may be derived from soil, sewage, or plant decomposition. The rate at which NO_3-N is reduced to N_2 during (heterotrophic) denitrification is largely dependent on the bioavailability of an electron donor (usually in the form of organic materials such as glucose, fructose, wheat straw, cellulose and plant litters), and could be utilized to enhance the denitrification efficiency in organic carbon-limited ditches (Lin et al., 2002). Previous studies reported that treatment systems can possibly utilize plant biomass or root release, as the source of carbon to maintain denitrification (Zhai et al., 2013). Other studies demonstrated that carbon source only from the root exudates of emergent plants is not enough to sustain a good treatment performance of systems.

7.1. Organic carbon amendments

The feasibility of supplying different carbon sources to improve potential denitrification rate in treatment systems has been widely studied in recent years. In their investigation on ditch sediments, Burchell et al. (2007) demonstrated increasing organic matter (e.g., straw) resulted in considerable increases in nitrate removal. Other studies used various organic materials in stream bioreactors and found that nitrate removal was in the following order: cornstalks > cardboard, >wood chips and oil > wood chips (Greenan et al., 2006; Liu et al., 2015). Liu et al. (2015) performed a pilot-scale field trial of organic carbon barriers in VDDs, and found rice straw provided high removal rate of nutrients (e.g., 73% for NH_4^+–N and 96% for NO_3^-–N). These authors also reported that the amount of rice straw supplied to VDDs was positively correlated with nutrient removal. Faust et al. (2016) examined effects of drainage ditch sediments with externally added organic matter (glucose or *Cynodon dactylon* hay) on NO_3-N removal and reported the removal of nitrate ranged from 83% to 100%. Studies on the relative performance of various carbon materials is therefore essential for a more informed choice of external electron donors to use in VDDs, based on the specific requirements of the system such as availability of nitrate concentrations, presence of anaerobic conditions, maintenance, availability of substrates, and cost. Taken together, these results suggest that amendments of organic carbon to ditch sediment enhance pollutant removal. Moreover, further investigations on the forms of organic carbon required for successful pollutant removal result are necessary.

8. Conclusions and future research needs

This review summarized studies on nutrients and organic pollutants removal in VDDs and to determine the most significant factors that influence pollutant removal processes. It has been widely acknowledged that VDDs are quite suitable for the treatment of nutrients and other pollutants from domestic sewage and agricultural runoff after years of research and implementation. This paper shows that much has been learned, much progress in the functional characteristics and dynamic management of VDDs has been made in removing major pollutants, and the long-term use of ditch treatment system has been improved as well. For instance, positive results in VDDs for in situ treatment of

untreated domestic sewage can be achieved by: (1) the installation of weirs within drainage ditches at multiple locations (e.g., appropriate HRT), (2) management strategies within VDDs, (3) plant typology, (4) choice of suitable sediment composition (gravel, sand, silt and clay particles), (5) organic carbon amendments, (6) pollutant loading rate and others. Fig. 3 synthesizes the major ruling functional characteristics of VDDs for domestic sewage and agricultural runoff. In a context of rapid socio-economic development, lifestyle, and environmental condition changes in rural regions, there has been an increased interest in assessing the suitability of VDDs for treating rural non-point source pollution. However, VDDs are still laced with some challenges, and further investigations and development studies are required. In summary (see also Fig. 3):

(1) The results of review on bed properties (substrates) and functional characteristics (types of plants and biofilm) indicate water quality improved within VDDs and also demonstrates strong interactions among plant species, substrates and microorganisms, which in turn influenced other processes. Therefore, these three components are still significant for the long-term operation of VDDs in reducing nutrients and other pollutants removal within VDDs. Hence, more attention is required for studies examining suitable plant species. Species with the following characteristics would be ideal: fast growth rate, high plant biomass, ability to grow in temperate and cold environments, easy harvesting and accumulation of a range of nutrients and organic pollutants in their aboveground biomass or any other harvestable plant biomass, and appropriate characteristics to survive under high pollutant levels and high pollutant removal capacity. Most recent studies have focused on the ability of ditches to remove nutrients from farm fields by comparing only the entrance and exit concentrations, which provide little insight into the expected performance of ditches. A rigorous investigation focusing on the abilities of various ditch plants to take up these pollutants under different climates is required, particularly for cold climates. Seasonal variations of pollutant uptake by plants, particularly in areas with important winter frost, are still limited in the literature, and further research is needed in this area. Research in regions with warm climates has seldom taken into account the winter months. In addition, substrate types which have high sorption capacity and are beneficial to removal processes is a research area that must be developed and utilized for VDDs.

(2) In addition to plants, substrates, and microorganisms, the review indicates that the optimal treatment performance of VDDs is critically dependent on low-grade weirs, environmental factors, maintenance, and seasonal variations. Therefore, future studies are recommended on how these parameters can be optimized to improve the function of ditches. Biomass productivity is one of the most noticeable and significant factors for characterizing the structure and function of drainage ditches. Harvesting of aboveground biomass from the ditch is an appropriate intervention to prevent release of pollutants in the dormant season (Kumwimba et al., 2016c; Kröger et al., 2007b).

(3) PPCPs in VDDs are removed as a result of complex processes. Currently, available studies on removal processes (e.g., sorption, plant uptake and biological degradation) are limited. Despite the widespread presence of drainage ditches, very few studies have assessed their role in the export of PPCPs and heavy metals. Furthermore, most studies were focused on chemical monitoring at the inlet and outlet to analyze the removal of certain organic pollutants (e.g., pesticides) within the ditches. Therefore, further research is sorely needed in order to describe and understand the removal pathways or fate processes of these pollutants in VDD systems.

To date the number of studies that have been conducted with two-stage ditches, effect of ditch length and ditch water level remains rather limited. Comprehensive studies assessing effects of these parameters on pollutant removal are necessary. Furthermore, a number of ditch characteristics can extensively change with ditch maintenance; a better understanding of the influence of the common maintenance activities (e.g., dredging, vegetation removal) on the performance of ditches to remove these pollutants is recommended for future research. Overall, a long-term investigation on the use of VDDs for treating domestic sewage and agricultural runoff under different ditch management practices will be required.

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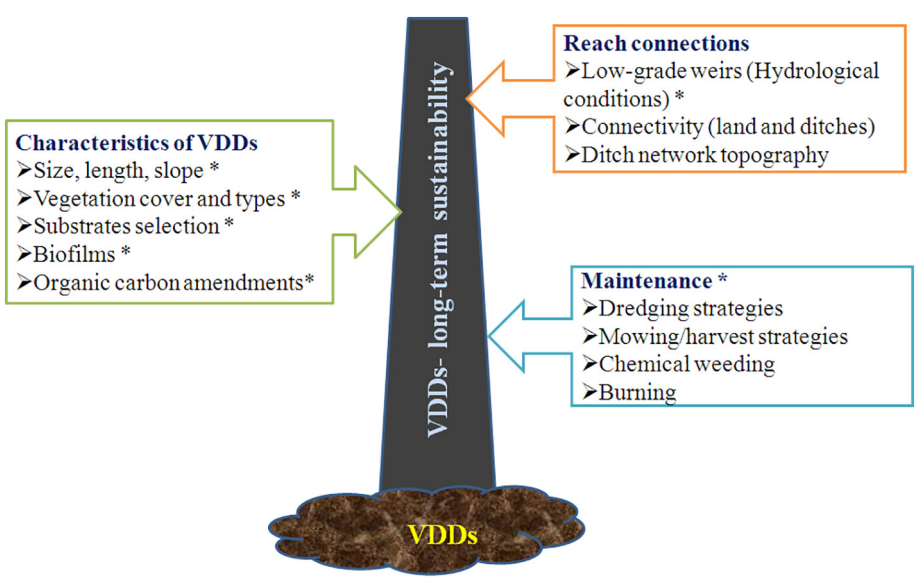

Fig. 3. Summary of research studies reviewed and future research needs for enhancing the sustainability of VDDs. (Asterisk represents areas where future studies are recommended).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.05.184.

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