



Review article

Performance assessment of local aquatic macrophytes for domestic wastewater treatment in Nigerian communities: A review

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ABSTRACT

The concept of treating wastewater before disposal is a global necessity. Recent mechanisms of doing this include the use of Constructed Wetland Systems (CWS). This technique is believed to be cost-effective and simpler compared to conventional methods. The application of this system is primarily dependent on the use of plants through the phytoremediation process. There is evidence of the potential of some locally found Nigerian aquatic plants such as water lettuce, water hyacinth and duckweed to be applicable for this purpose. However, there is little information on their performance level in remediating domestic wastewater. Thus, this review paper assessed the performance of these local macrophytes for domestic wastewater treatment and the potential of contributing the same in Nigerian communities. This was done by reviewing recent literature on the role of water lettuce, water hyacinth and duckweed, their occurrence and their efficiency in minimising different wastewater contaminants. Contaminant indicators such as total solids, electrical conductivity (EC), BOD, COD, dissolved oxygen, total phosphorous, total nitrogen, and heavy metals have been reduced using these macrophytes. The review indicates that the selected macrophytes do not only have the potential for wastewater purification but high efficiencies in doing so when applied appropriately in the Nigerian communities.

1. Introduction

Urbanization and population growth in developing countries have increased freshwater demand required to satisfy increased domestic and industrial needs. This in turn leads to increased wastewater generation (Dar et al., 2011; Zhang et al., 2014; Shingare et al., 2019). In most cases, the wastewater is usually discharged into the water bodies without pre-treatment or monitoring, which causes pollution, aggravates the scarcity of freshwater and often leads to the accumulation of sludge deposits in water courses (Rahman et al., 2020; Ajibade et al., 2013). The discharge of untreated effluents also leads to reduced dissolved oxygen (DO), increased nitrates and suspended solids and other organic contaminants in these water sources (Stefanakis et al., 2019; Ingraio et al., 2020). This consequently impacts surface and underground freshwater sources. Moreover, wastewater contaminants are likely to cause water-borne illnesses like diarrhoea, typhoid, cholera and poliomyelitis (Hoffmann et al., 2011). At the same time, its compounds lead to alteration of taste, colour and odour of the wastewater effluent-dominated rivers. In addition, these compounds increase the rate of deterioration of hydraulic

devices during wastewater conveyance for reuse purposes (EPA, 2004; Chen et al., 2016). Thus, it is now necessary to find appropriate ways to discharge the large quantity of wastewater that has become a major concern for individuals and governments globally in the 21st century. This will not only reduce pollution of water courses but recover wastewater which can be useful in various sectors of the economy, especially in irrigation and aquaculture (Olukanni and Kokumo, 2013).

Treatment methods commonly used are conventional wastewater treatment systems which include activated sludge systems, membrane bioreactors and membrane isolation systems. These systems demand a lot of energy for their mechanical components which results in a significant cost of operation, and maintenance and thus a drawback for many developing regions to invest in (Olukanni and Kokumo, 2013; Almuttar et al., 2018; Rahman et al., 2020). Thus, in recent times, the use of constructed wetlands which are capable of reducing pollutants in wastewaters is gaining prominence (Olukanni and Ducoste, 2011; Tan et al., 2019; Ji et al., 2020). These systems utilize physical processes, and chemical and biological interactions that are engineered to mimic the natural occurrences of wetland vegetation, thereby facilitating wastewater treatment

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(Nayanathara and Bindu, 2017; Babatunde et al., 2016; Ji et al., 2020; Maine et al., 2007; Olukanni and Ducoste, 2011; Vymazal, 2011; Badejo et al., 2017). They have been confirmed to serve as a robust sustainable technology with a huge capacity to treat wastewaters and a viable decentralized system to manage domestic wastewater in developing nations (Olukanni and Ducoste, 2011; Olukanni and Kokumo, 2013; Tan et al., 2019; Vo et al., 2019). Moreover, constructed wetlands appear to be more effective than conventional treatment techniques with a higher ability to remove pollutants and are advantageous in terms of low maintenance costs and energy demand (Zhang et al., 2014).

1.1. The role of aquatic plants (macrophytes) in wastewater treatment

As earlier stated, the most important component of the CWS are macrophytes; plants that grow and spend most or all of their lifecycle in or around water. Their major role in CWS is achieved by the ability to undergo a phenomenon known as phytoremediation. This is the characteristic capacity of plants to remove pollutants and contaminants from various natural and artificial wastewater sources (Priya and Selvan, 2014). It is this ability of macrophytes, coupled with their fast growth rate and the economic benefits of CWS in general that have caught the interest of researchers around the world (Badr El-Din & Abdel-Aziz, 2018). Consequently, more investigations are advancing on the potentials and efficiencies of different species of macrophytes for the treatment of different concentrations of wastewater including those from industrial, aquaculture and municipal/domestic sources. Particularly, interests have been geared toward exploring the fact that different macrophytes have different levels of pathogen removal, adaptations to different climatic conditions, and resistance to physicochemical variances (Alufasi et al., 2017; Tan et al., 2019; Rahman et al., 2020). Hence, the results of a particular geographical location may be different from another. Thus, this paper intends to contribute to this field of research by exploring the performance of local aquatic macrophytes (water hyacinth, Water lettuce and duckweed) for domestic wastewater treatment and the potential of contributing the same to Nigerian communities. It is understood that quite a number of research exist in this area, however, the aim of this review paper was to bring to bear the importance of the role of local macrophytes in ensuring sustainability in domestic wastewater treatment in Nigerian communities. This study is the first step of research that the authors are currently involved in with regard to the sustainability of wastewater treatment technology and was developed for the reason of creating a tool for rapid information diffusion. In addition to the introduction, recent papers were reviewed under 7 major keywords; Wastewater treatment, Constructed wetlands, Sustainable technology, Aquatic macrophytes, wastewater contaminants, and Phytoremediation. Relevant information on the performance of these Nigerian-based aquatic macrophytes was discussed, as well as the prospects for optimum results when used as constructed wetland plants.

2. Selection of macrophytes for wastewater treatment

Macrophytes are a vital part of the complex system of chemical exchange in a water body which influences the supply of oxygen in the water (Uka and Chukwuka, 2011). They are also a significant design component in natural and constructed wetlands which defines it as green technology (Villa et al., 2014; Stefanakis et al., 2014). Pollutants in wastewater can be absorbed by macrophytes and stored in their tissue, providing microorganisms and aerobic conditions through oxygen transfer to their root zone to improve pollutant breakdown (Gorito et al., 2017; Almuktar et al., 2018). While some reports such as Scholz (2006) may not agree with this, some reports have verified this and revealed the significant effect of macrophytes enhancing high pollutant removal in wetland treatment systems (Vymazal, 2007; Ha et al., 2011; Ko et al., 2011; Paola and Elena, 2014; Almuktar et al., 2018 and de Anda et al., 2018). Nonetheless, the choice of local macrophyte species that can tolerate conditions of a

particular region is very vital in attaining optimum results (Wu et al., 2015).

Macrophytes may be grouped into four (4) basic types that include submerged, emergent, floating leaf, and freely floating (Rezania et al., 2016). The emergent types can be seen at a significant height above the water surface, have their roots planted in soil and greatly stabilize substrate, while the floating leaf types, their roots get static in the saturated media with their whole body above the water surface (Wu et al., 2015; Rezania et al., 2016). The immersed macrophytes may need oxygenated water for better growth because their photosynthetic parts are underwater. The free-floating types such as *Lemna minor*, *Eichhornia crassipes*, *Pistia stratiotes* and *Hydrocharis dubia* which drift on the water surface are characterized by a high capacity of nitrogen, phosphorous, suspended solids and heavy metals removal rates from wastewater (Al-Hashimi and Joda, 2010; Selvarani et al., 2015; Shafi et al., 2015; Wu et al., 2015; Rezania et al., 2016; Gatidou et al., 2017).

Three macrophytes (i.e. water hyacinth, water lettuce and duckweed plants) have been chosen for this study to enable reduce the gap in knowledge with regards to scarce information on the characteristics and performance of indigenous species of macrophytes for pollutant removal. While it is obvious that water hyacinth is being used and studied to some extent in Nigeria as reported (Ekelemu, 1998; Gunnarsson and Peterson, 2007; Uka and Chukwuka, 2011; Ajibade et al., 2013; Olukanni and Kokumo, 2013), there is need to understand the potential of other species and even compare their abilities. Moreover, the three species have been observed to be easily found in Nigerian water courses, such as in Kainji River Basins, Ogudu area in Lagos and Uju in Ogun state. In addition, their morphology and root physiology could be suitable for Surface Flow CWs.

For plants to carry out phytoremediation efficiently, maximum growth of the plant is very vital. Environmental factors such as temperature, solar radiation, the salinity of water etc., affects their growth and performance. The selected plants can survive and flourish under high temperatures, and nutrients concentration, tolerate drought and a wide range of pH values and also grow very fast (Fonkou et al., 2002; Gupta et al., 2012; Gul et al., 2017; Ceschin et al., 2019). This means they can easily be cultured over a short period of time. These macrophytes, especially Water hyacinth and Water lettuce are also invasive in nature (Uka et al., 2007; Odedishemi, 2009; Gupta et al., 2012; Gul et al., 2017; Ekperusi et al., 2019), which could hinder economic activities such as sailing and fishing where their population dominates. Hence, researchers and investors can take advantage to reduce and eliminate the cost of destruction by putting them into beneficial use.

3. Pollutant removal efficiencies of the selected macrophytes

Research shows that the most frequently applied aquatic macrophytes for heavy metal elimination includes water lettuce, duckweed, and water hyacinth. The capacities of these three free-floating aquatic macrophytes in removing heavy metals are shown in Table 1. Over the past decade,

Table 1. Heavy Metals Removal Rate of the selected macrophytes Aquatic Macrophytes.

Aquatic macrophytes	Metals	Peak Removal rate (%)
<i>Eichhornia crassipes</i> *	Fe, Cu, Zn and Cd, Cr	80.00
<i>Azolla</i> Spp	Hg	93.00
<i>Ceratophyllum demersum</i>	Zn, Pb and Cu	80.00
<i>Ipomeae aquatic</i>	Hg	90.00
<i>Lemna minor</i> *	Pb, Zn, Mg, Cu, Ca, Cd	90.00
<i>Ludwigia repens</i>	Hg	99.00
<i>Pistia stratiotes</i> *	Hg, Cr and Cd	85.90

Sources: (Srivastava et al., 2008; Swarnalatha and Radhakrishnan, 2015; Showqi et al., 2017; Rai, 2019). NB: Bold* = selected aquatic macrophytes.

quite a lot of published works regarding pollutants removal of macrophytes focus on characteristics, mechanisms and mode of applications (Gupta et al., 2012; Selvarani et al., 2015; Rezanian et al., 2016; Nayana-thara and Bindu, 2017; Ting et al., 2018; Iqbal et al., 2019; Rai, 2019). This review explores the effectiveness of these three plants which are known as hyper-accumulators of different types of pollutants.

Several research studies have indicated variations in pollutant uptake and removal capacity of macrophytes. Recently, Almuktar et al. (2018), examined the capacity of four emergent macrophytes in treating contaminated river water. As expected, there was disparity, especially in nitrogen and phosphorus elimination rates. Nonetheless, the wetland design parameters; HRT, loading rate, weather conditions and system arrangement played a part. Elsewhere, the results of Ha et al. (2011) on heavy metal removal rates of three plants indicated outstanding positive performance that provided effluent wastewater suitable for public discharge and irrigation. Although, it was observed that apart from the plant species, heavy metal bioaccumulation also depends on the root system of the plants (Yadav et al., 2012). They pointed out that the root system is more effective than the shoot system of the plants but periodic harvesting of the later parts would significantly improve its bio-accumulation capacity. This assertion helps to buttress an earlier recommendation that regular harvesting of plant leaves will increase, thereby maintaining nutrient elimination in the constructed wetland systems (Vymazal, 2007). One most recent study; Ma et al. (2020), also noticed differences in the remediation performances of 11 macrophytes including *Eichhornia crassipes* on Pb and Cr contaminated sediment through batch pot experiments. Thus, conscious data-based macrophyte selection is vital to ensuring a robust biological sewage treatment project.

3.1. Water hyacinth (*Eichhornia crassipes*)

Eichhornia crassipes (Figure 1) is one of the most widely dispersed free-floating aquatic macrophytes, with its presence well documented in Africa (Ekelemu, 1998). It may be considered the most dominant and researched aquatic plant in Nigeria (Ogunlade, 1992; Adekoya, 2000; Gunnarsson and Peterson, 2007; Olukanni and Aremu, 2008; Uka and Chukwuka, 2011; Ajibade et al., 2013; Olukanni, 2013). From these reports, it could be posited that the spread of water hyacinth has been fueled by activities such as the discharge of sewage and all kind of wastewater. The population of water hyacinth will double within 5 and 15 days given favorable conditions, while its biomass can weigh up to 25 kg per square meter if completely undisturbed and the seeds remain viable for up to 15 years in water, silt or mud (Odedishemi, 2009).

Due to these characteristics and more, interest in water hyacinth for phytoremediation has evolved over the years (Ajibade et al., 2013; Swarnalatha and Radhakrishnan, 2015; Rezanian et al., 2016; Priya and Senthamil, 2017). Its treatment capacity has been separately investigated severally and in combination with other plants, showing convincing results (Table 2). For instance, when studied together with water vetiver grass and water lettuce, it produces good and better results than others in

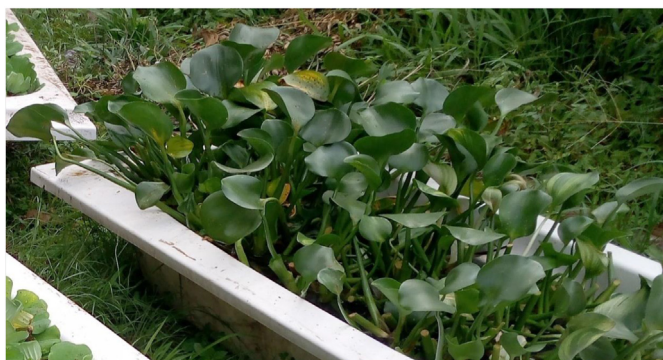


Figure 1. Water hyacinth (*Eichhornia crassipes*).

Table 2. Summary of Pollutant Removal Capacity of Water hyacinth.

Pollutants	Duration (TMT)	Wastewater type	Removal rate (%)	Reference(s)
Turbidity, TSS, TDS, EC, Hardness, COD, BOD, P, TN	15–21 days	Domestic	67, 45, 20, 28–50, 33–60, 27, 30–60	Badr El-din and Abdel-Aziz, 2018; Dar et al. (2011),
Cl ⁻ , Mn, Pb, K, F Nitrate, Sulphate	35 days	Domestic	63, 84, 95, 90, 89, 99.7, 65	Ajibade et al. (2013)
Organic contaminants (BOD, COD, TP, TN, etc.)	31 days–1 year	Different types	Average 50–90%	Gupta et al. (2012)
DO improvement, COD, BOD, (NH ₃ -N) and TSS	21 days	Domestic	47% improvement 38–90 reductions	Rezanian et al., 2016
Turbidity, BOD, COD, TSS, TDS, Nitrates, Pb, TN	31 days and 1yr	Industrial and Domestic	92.5, 86, 79–83.7, 91.8, 62.3, 67.5, 83.4, 77	Fazal et al., 2015, and Valipour et al., 2015

TMT: Treatment period.

eliminating all kinds of contaminants in wastewater (Dar et al., 2011; Akinbile and Yusoff, 2011; Gupta et al., 2012; Rezanian et al., 2016; Saha et al., 2016). A study at Ologe Lagoon, Lagos, on the passive phytoremediation of water hyacinth also revealed that it can bio-accumulate heavy metals (Ndimele and Jimoh, 2011). Most of the studies conducted in Nigeria reported similar treatment and removal efficiencies between 38% to 96% for DO, COD, NH₃-N, BOD and TSS obtained by Rezanian et al., 2016 and Ting et al. (2018).

3.2. Water lettuce (*Pistia stratiotes*)

As shown in Figure 2, Lettuce is a free-floating aquatic plant belonging to the Araceae family. With the roots hanging and submerged in water, the leaves float above the surface of the water. It grows at a minimum temperature of 15 °C with a growth rate somewhat faster than that of water hyacinth in the dry season. Conversely, the rainy spell lowers the growth rate due to minimal solar radiation available for its activities (Gupta et al., 2012). This makes it a suitable macrophyte for wastewater purification in Nigerian communities. Despite not yet being widely investigated as water hyacinth, it has shown great potential to remediate different kinds of wastewater pollutants (Table 3).

A pilot study by Lu (2009) showed that water lettuce growth resulted in a reduction in EC as a result of salt removal from the waters by plant root adsorption. Also, turbidity, NH₄-N, total solids, NO₃-N, total nitrogen and other nutrient concentration were reduced to optimum levels. Consequently, the water quality of the treatment reactor was greatly improved due to phytoremediation by water lettuce.



Figure 2. Water Lettuce plant.

Table 3. Summary of Pollutant removal Capacity of Water lettuce.

Pollutants	Duration	Source	Removal rate	Reference(s)
TDS, COD, BOD Faecal coliforms, Nitrate, TP, NH ₃ -N	6 months	Domestic	70, 59, 93, 99, 70, 33, 95%	Awuah et al. (2004)
Turbidity, COD, TKN, NO ₃ ⁻ , NH ₃ , PO ₄ ³⁻	30 days	Agriculture	92.07–93.69 % reduction for all parameters	Akinbile and Yusoff, 2011
COD, TN, TP	30 days	Domestic	45.71, 58.27, 46.56	Qin et al. (2016)

In addition (Lu et al., 2010), observed that total suspended particles in the water column were reduced by around 10% in treatment plots compared to control plots. Also, the growth of water lettuce resulted to a fall in the pH of the water, even though it was not expected because usually, plant photosynthesis raises the pH of water.

The result of a study found increased concentrations of selenium in the leaves and roots of the plant after a feasibility study of a hydroponic system to produce selenium-enriched water lettuce for animal feed (Uka and Chukwuka, 2011). This implies that water lettuce has a high capacity for heavy metals absorption.

3.3. Common duckweed (*Lemna minor*)

Common duckweed (Figure 3) could be described as a tiny free-floating leaf plant that usually forms a layer of blanket-like covering on any nutrient-filled water surface. It is a kind of stem-less plant which is majorly a combination of a few leaves or fronds and a single root. Being a monocotyledonous plant, it undergoes vegetative reproduction through simple division that enables it to form different separate plants. It is believed to have originated from Africa, Europe, Asia and North America but is dominant in South America and Australia (Appenroth et al., 2015). Due to its invasive nature, *Lemna minor* usually creates ecological and economic concerns wherever there is a cluster of plants (Ekperusi et al., 2019). Still, the plant is widely reported to be one of the successful and extensively used free-floating macrophytes for the phytoremediation of different types of chemical and organic pollutants. This has been justified by using the plant separately or with other aquatic macrophytes (Mohedano et al., 2012; Ekperusi et al., 2019; Zhou et al., 2019).

The ability of duckweeds to withstand high nutrient concentration, temperature and pH value, enables it to provide efficient phytoremediation of various wastewater when used in constructed wetland systems. In a single study, where primary and supplementary treatment processes could only guarantee 50% BOD₅ and phosphate reductions, duckweed was able to reduce these elements to about 94.45% and 79.39%, respectively (Priya et al., 2012). In addition, as a result of duckweed's increased nutrition load, total nitrogen and phosphorous removals were 98% and 98.8%, respectively, with an improved dissolved oxygen level (Mohedano et al., 2012). These reports concluded that

**Figure 3.** Common duckweed plant.

duckweed was extremely effective at removing organic pollutants from aquatic habitats, particularly for the treatment of industrial and agricultural effluents.

Duckweed has the ability to eliminate or decrease organic contaminants in wastewater effluents regardless of the effluent type (Ekperusi et al., 2019). The accumulation of biomass and protein matters in the duckweed plant tissue reflects the elimination of organic pollutants (Mohedano et al., 2012; Saha et al., 2015). This indicates that the plant is using nutrients from the effluents to grow and thrive. However, a report reveals that the concentration of some metallic ions may affect the removal efficiency of duckweed. For instance, the study by Zhou et al. (2019) shows that remediation of ammonia nitrogen (NH₃-N) and total phosphorus (TP) by duckweed was elevated at 0.1–1.0 mg/L and lowered at 2.0–5.0 mg/L of Cu²⁺. Thus, there may be a need for models to optimize the concentrations of the ions to improve or maintain good treatment performance. The summary of treatment capacity of duckweed for various pollutants at different concentrations is shown in Table 4.

Mohedano et al. (2012) observed a 35 percent rise in plant biomass and a 35 percent increase in protein content, whereas, Saha et al. (2015) reported a 30 percent increase in duckweed biomass in just 21 days. Depending on the number of pollutants and the toxicity of the effluents type, there was poor performance (Saha et al., 2015) and inhibition (Wang et al., 2017) of duckweed performance. The potential of duckweed plants to remove chloride (30%), sulphate (16%), and total dissolved solids (14%) from steel effluents was demonstrated in a 21-day trial with steel effluents (Saha et al., 2015). This is quite low compared to the reports of more recent scholars (Amare et al., 2018; Tufaner, 2018) who observed high removal percentages of at least 60% (Table 4). This could be accrued to many factors such as Pollutant concentrations in effluents are high. Similarly, the plant showed a slight inhibition of 2300 mg L⁻¹ COD concentration within 5 days of observation (Grijalbo et al., 2016). This means that the plant has the potency to resist high levels of pollution in the environment. It also strengthens the plant's resistance to contaminants. Albeit, the study was only conducted for a brief time which may have contributed to a little inhibition. As a result, it is possible that prolonging the research period would be preferable. For instance, Papadopoulou and Tsihrintzis (2011) used over a year to assess the phytoremediation capability of *Lemna minor* in removing organic pollutants from sewage effluent. The results were quite impressive with high removal rates for BOD, NH₃, and TSS at 94, 72, and 63%, respectively. Arguably, the results were still beyond expectation for organic pollutant removal of duckweed plants, especially with the slight increase in phosphate level. Nevertheless, a recent researcher; Tufaner (2018) reported an over 82% reduction of both BOD, COD, TN, ammonium nitrate and phosphate. Lastly, reports shows that duckweed can be used for treatment of different kinds of effluents successfully (Table 5).

4. CWS for optimal application in Nigerian communities

The application of aquatic macrophytes in wastewater treatment in artificial wetland systems is still relatively new in Nigeria. Albeit, quite some areas including the characteristics, advantages and weaknesses of using Constructed wetland systems and the macrophytes' capacities and efficiencies in pollutant removal have been researched (Ogunlade, 1992, Adekoya, 2000, Gunnarsson and Peterson, 2007; Uka and Chukwuka, 2011; Olukanni and Ducoste, 2011; Ajibade et al., 2013 and Olukanni, 2013; Isiorho et al., 2014). However, there is a need for information on constructed wetland systems that best fits the climatic condition of the region.

A wetland is a complex ecosystem that involves the interaction of plants, water, a substrate (e.g. litter, sand and gravel) and microorganisms. While the wetland system occurs naturally, a constructed wetland system is a natural system designed to mimic the arrangement and occurrences of a natural wetland in order to improve wastewater quality through the following processes;

Table 4. Summary of pollutants removal rate of *Lemma minor*.

Pollutants	Duration	Concentration	Removal rate	Reference(s)
EC, TDS, Turbidity, COD, BOD, P, TN, SO ₄ ²⁻	21–28days	452–2737 mg L ⁻¹	68,68,97,43–92,42-97,94.6, 77.9%	Amare et al. (2018), Badr El-din and Addel-Aziz, 2018
EC, Turbidity, TDS, Cl, hardness, Ca, Mg, Nitrate, Sulphate,	30 days	0.83 µS/m, 89.6 NTU, 1.7–525 mg L ⁻¹	33.7,93.1,35.2,61,45.7,32.3,55.9,77.6%	Farid et al. (2013)
COD,	5 days	2300 mg L ⁻¹	16%	Grijalbo et al., (2016)
TN, N–NH ₃ , TP	1yr	264.5, 2020.1, 30.1 kg L ⁻¹	98.3, 98.8,94.5%	Mohedano et al. (2012)
COD, BOD, TKN, NH ₃ -N, TP,PO-P	25 days	1025, 167, 76, 55, 4.8, 2.4 mg L ⁻¹	88,83,94,96,97 & 95%	Tufaner (2018)
N, P	9 days	1020, 224 mg L ⁻¹	60–67.84%	Zhang et al., 2014
NH ₃ , NO ₂ , NO ₃ , PO ₄ , BOD and COD	31 days	Domestic and Industrial	96, 98, 98, 96, 79 and 79%	Selvarani et al. (2015)

- i. Settling of suspended undissolved solids particles,
- ii. Filtration and chemical precipitation of organics as the water interacts with the substrate,
- iii. Chemical transformation (adsorption and ion exchange on the surfaces of plants and substrates)
- iv. Pollutant breakdown and transformation by microbes and plants
- v. Nutrient uptake and transformation by microorganisms and plants (Gorito et al., 2017)

Constructed Wetlands are characterized basically by the water level in the system; i.e., either a free water surface flow (FWSF CW) or a subsurface flow system (SSF CW) (Hoffmann et al., 2011; Vymazal 2014; Stefanakis et al., 2014; Almukhtar et al., 2018). In the former, the water flows freely above the treatment media, while in the latter, wastewaters flow below the media. Hybrid CWS are a mix of horizontal and vertical flow CWS, which are fed with influents horizontally and vertically, respectively (Vymazal 2013, 2014; Wu et al., 2014; Stefanakis et al., 2014). Unlike the horizontal flow types, vertical-flow CWS achieve more oxygen transfer rate (Fan et al., 2013; Li et al., 2015; Zhi et al., 2015). This is accrued to the additional aeration provided by the gravity feeding of the system (Stefanakis et al., 2014; X. Song et al., 2015).

Notwithstanding, horizontal-flow types are highly efficient in treating different kinds of wastewater (Paing et al., 2015). Nevertheless, their biggest weakness lies in the fact that due to insufficient aeration and interaction of the wastewater and substrates there is poor phosphorus elimination (L. Song et al., 2015; Stefanakis et al. (2014) (Almukhtar et al., 2018). The only problem with vertical flow CWS is the biological or physical clogging which affects their treatment efficiency and degrades macrophytes and subsequently affects the treated wastewater quality (Almukhtar et al., 2018). These variations in the two systems necessitated the design of a hybrid system, but with a focus on obtaining higher nitrogen removal and capacity to treat different wastewater types (Ayaz et al., 2012; Comino et al., 2013; Vymazal, 2014).

Submerged, floating leaf, free-floating, and bottom rooted or emergent macrophytes cover an exposed aquatic area in FWSF CWS, whose operation is similar to natural wetlands (Wu et al., 2014; Almukhtar et al., 2018).

Since water hyacinth, water lettuce and duckweed are all free-floating macrophytes, they can easily be utilized with FWSF CWS to take advantage of the following qualities of these types of treatment cells:

- i. They are great at eliminating suspended particles and nitrogen, heavy metals, BOD, COD, and pathogens (Tilley et al., 2014; Almukhtar et al., 2018).
- ii. They are also suitable for warm climates due to the position of macrophytes above the water surface which reduce the high rate of evaporation (Tilley et al., 2014).
- iii. They provide an aesthetically pleasing environment as the position of macrophytes above the wastewater surface reduces odour and provides green vegetation

- iv. They can be built and repaired with locally available materials with very little electrical energy requirement since most flows are by gravity.
- v. Ultimately they require very little design and running costs (Tilley et al., 2014)

4.1. Requirements for utilizing macrophytes in CWS

Prior to the exploration of CWS using water lettuce, water hyacinth, and duckweed to purify wastewater, it is vital to pay attention to some operational conditions, such as hydraulic retention time, water depth, plant density, environmental factors as well as management like regular harvesting to keep the plant young/fresh (Ting et al., 2018). It is required that CWS are operated when conditions are favourable for macrophytes growth because high treatment efficiency is highly influenced by the rate of plant growth (Rezania et al., 2016). For instance, the growth of water hyacinth is influenced by several factors, such as intraspecific competition, size limitations, and internal and external environmental factors like water air temperatures, ambient nutrients, and solar radiation (Ting et al., 2018). Just like water hyacinth, plants are generally high temperature sensitive, thus these three plants are highly recommended for use in subtropical and tropical regions like Nigeria for wastewater treatment (Nahlik and Mitsch, 2006; Tilley et al., 2014; Ting et al., 2018).

It is a well-known fact that climatic change affects the activity of plants; for example the higher the air temperature and sun radiation, the greater the rate of photosynthesis and plant productivity. Additionally, Table 6 shows the summary of some of the design criteria and requirements of constructed wetland for maximum results. The higher the depth of water, the lower the oxygen concentration and its transfer by the plant roots, and as a result, the facultative zone is enhanced thereby allowing anaerobic microbial growth to flourish (Vymazal, 2007). Thus, a shallow constructed wetland system with water hyacinth, water lettuce and duckweed is suggested as a solution to the anaerobic zone problems (Wu et al., 2015).

Table 5. Recent studies reporting various contaminants removable by duckweed.

Types of Contaminants Removed	Sources
Agrochemical Effluents	Dalton et al. (2013), Wang et al. (2017), Panfili et al. (2019)
Pharmaceuticals and Personal Care Effluents	Qu et al. (2018), laTrout et al., 2017
Radioactive Contaminants	Van Hoeck et al. (2015); Van Hoeck et al., 2017; Horemans et al. (2014); Horemans et al. (2015); Favas et al. (2016); Sasmaz et al. (2016).
Nanomaterials	Song et al. (2015), Song et al. (2016); Chen et al., 2016; Tarrahi et al. (2017), Ergen and Tunca (2018)
Petroleum Hydrocarbons	Ndimele (2010); Bhaskaran et al. (2013); Yavari et al. (2015); Gatidou et al. (2017)

Table 6. Recommended design parameters for and operating CWs.

Design parameter	Standards	
	FWSF CW	SSF CW
Size of the reactor (m ²)	Should be large as possible	<2500
Ratio of Length to the breadth	3:10 to 3:50	<3:10
Depth of water (m)	0.30 to 0.50	0.40 to 1.60
Slope (%)	<0.50	0.50 to 1.0
HLR (m/day)	<0.10	<0.50
HRT (days)	5.0 to 30.0	2.0 to 5.0
Substrates	Natural or industrial by-products with a porosity between 30–50% and <20 mm and 50–200 mm particle size for the influents and effluents respectively.	
Vegetation	Local varieties at a plant density of 80% are preferable	

FWSF = Free Water Surface Flow. SSF = Sub-Surface Flow CW. HLR = hydraulic loading rate. HRT = hydraulic retention time. Source: (Wu et al., 2015)

4.2. Case studies of the application of aquatic macrophytes in CWS in Nigeria

A passive phytoremediation study was carried out at Ologe Lagoon, Lagos by Ndimele and Jimoh (2011). The study showed that *Eichhornia crassipes* can accumulate heavy metals from wastewater even when their concentration in a given sample is low. This is an indication of the sensitivity and potential of this macrophyte specie to remediate polluted waters. Elsewhere in Covenant University, Ota Nigeria, the use of water hyacinth (*Eichhornia crassipes*) for their domestic wastewater treatment have been employed and its efficiency investigated on two different occasions (Olukanni and Kokumo, 2013; Isiorho et al., 2014).

The two reports are very impressive with high organic pollutants removal efficiencies. The first report assessed the efficiency of the existing constructed wetland that uses water hyacinth, also known as water Hyacinth reed bed (WHRB). By analyzing effluents samples from six WHRB reactors, among other parameters, there was a high performance of 70% of BOD, 68% of COD, 41% of Total Solids (TS) and 100% of zinc removal. However, the second study suggested that the constructed wetland may not be effective as expected due to the aeration and residence time of wastewater in the reactors.

Also, Ajibade et al. (2013) reported a study, carried out at the University of Ilorin, Kwara state on the phytoremediation efficiencies of water hyacinth in removing heavy metals in domestic sewage. In this study, plastic drums were used as wetland reactors to culture water hyacinth plants. The result of the experiment showed that metals such as; Cl-, Fe, Cu, Mn, Pb, K, F-, Nitrate and Sulphate were significantly reduced by at least 64%. This notwithstanding, plant density was a significant factor whereby high density purified more than moderate and low densities.

Edaigbini et al. (2015) use water hyacinth and water lettuce in a treatment pond to remediate polluted water obtained from a detention pit in the Niger Delta region of Nigeria. In addition, comparison was made of their effectiveness in remediating the water with standard discharge limits as a guide. Although the analysis showed that the majority of the parameters were above the permissible limits, there were some positive results and water hyacinth was found to be better in remediation of the produced water. The authors then recommended that for better results, the growth of macrophytes should be improved with fertilizers and occasional removal of dead plant parts to maintain optimum plant density and prevent contaminants return to the treatment system.

4.3. Future prospects for Nigerian communities

This study reveals that water hyacinth, duckweed and water lettuce as some of the local Nigerian aquatic macrophytes that have shown great potential for wastewater purification. Moreover, several works of literature have documented their effectiveness in organic, chemical, and heavy metals reductions (Wu et al., 2015; Rezanian et al., 2016), which means

they are vital tools for containing carcinogenic problems from water pollution. Also, since plant applications in wastewater treatment are mainly focused on domestic wastewaters, it is a promising avenue for Nigerians to explore this growing technology of using macrophytes to treat their domestic wastewaters at different levels (institutional, government and individuals). This is because these plants are not difficult to locate. For instance, the study shows that duckweed (*Lemna minor*) can be found in basically any stagnant water, and water hyacinth and duckweed are usually along slow-moving rivers and lakes (Uka and Chukwuka, 2011), while water hyacinth, water lettuce, duckweed and other dominant aquatic macrophytes can be found in Kainji lake basin (NIFFR, 2000).

The physical survey also revealed that water hyacinth and duckweed plants are in large numbers in Ogudu and Ota area of Lagos and Ogun state, respectively. Water lettuce (*Pistia Stratiotes*) plants were also spotted in Ota environs around Iju river banks. As earlier iterated, all the plants are capable of multiplication within a short period once given a favourable condition and nutrient availability.

It is still worrisome that most studies end at laboratory-based stages where prevalent environmental conditions may be controlled or influenced. Hence, field experimentation of constructed wetlands would provide a better understanding and real-time behaviour of these plants for sewage treatments. In addition, more research is needed to assess the efficiency of these plants (i.e. water hyacinth, water lettuce, and duckweed on both pilot and industrial scales. This is because the tolerance and removal levels of these plants to many contaminants remain unknown. Hence more research could be conducted to upgrade the process for industrial applications.

5. Conclusion and recommendations

Using CWS with aquatic macrophytes for wastewater treatment is observed to be growing. This is attributed largely to its set-up economic advantage, simplicity, little maintenance requirements and biodiversity preservation capacity. Many research scholars have applied water hyacinth, duckweed, and water lettuce in the reduction of wastewater pollutants, albeit their treatment abilities rely on various factors like climatic location and influent concentrations. The study observed that the efficiency of pollutant removal for a parameter such as TSS, BOD, TDS, COD, EC, and metals differs from one plant to another. Contaminant removal rates are also influenced by the growth of the plant and hydraulic retention times. Therefore when properly applied in CWS, water hyacinth, water lettuce and duckweed are reliable options for the treatment of domestic wastewaters and control of pollution in Nigerian communities. For instance, researchers have recommended that the initial wastewater characteristics should be checked before introduction to the plants as it can inhibit their growth. Also, it is advisable to acclimatize the plant for some time once they are moved from its original location. For maintenance purposes, the leaves of the plants must be harvested regularly to ensure an active plant shoot system which enhances proper metabolic activities and more nutrient absorption.

Declarations

Author contribution

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Data availability

Data will be made available on request.

Declaration of interest

The authors declare no conflict of interest.

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