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Chapter 20
Use of the Macrophyte *Cyperus papyrus* in Wastewater Treatment

Njenga Mburu, Diederik P.L. Rousseau, Johan J.A. van Bruggen, and Piet N.L. Lens

Abstract *Cyperus papyrus,* commonly referred to as papyrus, belongs to the *Cyperaceae* family and is one of the most prolific emergent macrophytes in African subtropical and tropical wetlands. Botanical studies have shown that stands of papyrus are capable of accumulating large amounts of nutrients and have a high standing biomass. Its C_4 photosynthetic pathway makes *C. papyrus* highly productive with dry weight biomass generation rates of up to 6.00 kg m^{-2} $years^{-1}$ and nutrient uptake rates of up to 7.10 kg $ha^{-1}days^{-1}$ and 0.24 kg $ha^{-1}days^{-1}$ of, respectively, nitrogen and phosphorus. *C. papyrus* plants take about 6–9 months to mature with a highly reliable natural regrowth and replenishment on a site after harvesting. Studies featuring side-by-side investigations with unplanted controls show that *C. papyrus* has mostly a positive effect on the treatment of wastewater. The ability of *C. papyrus* to use nutrients from the wastewater and the incorporation of heavy metals and organics into its phytomass, added to its easy management by regular harvesting, makes it one of the most suitable plants to be used in wastewater phytoremediation in tropical areas. Therefore, it continues to be an excellent candidate for application as a macrophyte in the constructed wetland wastewater treatment technology. As such, determining the potential scope of the performance of *C. papyrus* is vital for the optimal application and design of *C. papyrus*-based constructed wetland systems. This work collates growth, productivity and performance information from various independent studies incorporating the *C. papyrus* macrophyte.

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Keywords *Cyperus papyrus* • Tropics • Harvesting • Biomass • Tropical wetlands

20.1 Introduction

In the subtropical and tropical climate, *C. papyrus* is one of the most interesting macrophytes because it is amongst the most productive plants in wetlands (Kansiime et al. 2005; Heers 2006; Perbangkhem and Polprasert 2010). This plant has a high potential of producing biomass from solar energy, which is one of the recommended criteria for the selection of macrophytes in tropical areas with abundant sunshine for use in constructed wetlands (Perbangkhem and Polprasert 2010). The papyrus vegetation has been shown to actively improve wastewater quality through contribution to the removal of organic compounds (Vymazal and Kröpfelová 2009), heavy metals (Sekomo 2012), pathogens (Okurut 2000; Kansiime and Nalubega 1999) and excess nutrients such as nitrogen and phosphorus (Kansiime et al. 2007a, b, Perbangkhem and Polprasert 2010). This could be attributed to their ecological characteristics of high phytomass, well-developed root system and high photosynthetic rate (Jones 1988; Muthuri et al. 1989; Kansiime et al. 2007a). Various authors have presented experimental research findings on aspects of the characteristics of *C. papyrus* that have an influence on water quality improvement, both in the natural and constructed wetlands. This chapter collates these findings by answering the following questions related to the application and management of the macrophyte *C. papyrus* in wastewater treatment:

(a) What is the growth habitat of *C. papyrus* macrophytes, its morphology and physical effects on water quality improvement including the surface area for attachment of microbial growth?
(b) What is the influence of the metabolism of *C. papyrus on* water quality improvement (i.e. the plant nutrients (nitrogen and phosphorus) uptake potential, the root oxygen leakage and the biomass productivity)?
(c) What is the harvesting practice and the regeneration capacity for *C. papyrus* after harvesting?

20.2 Influence of Macrophyte on Pollutant Bioconversion and Removal in Treatment Wetlands

The biogeochemical cycling and storage of nutrients, organic compounds and metals in natural wetlands is mimicked in constructed wetlands, through the use of plants, porous media and associated microorganisms (Sonavane et al. 2008; Hunter et al. 2001). The presence of emergent macrophytes is one of the most conspicuous features of constructed wetlands, and their presence distinguishes constructed wetlands from unplanted soil filters or lagoons (Vymazal 2011; Greenway 2007). Their positive role on the performance of constructed wetlands has been well established in numerous studies measuring treatment with and without plants

(Kadlec and Wallace 2009; Brisson and Chazarenc 2009; Akratos and Tsihrintzis 2007; Yang et al. 2007).

Generally, the performance of wetlands for wastewater treatment depends on the growth potential and ability of macrophytes to develop sufficient root systems for microbial attachment and material transformations and to incorporate nutrients into plant biomass that can be subsequently harvested for nutrient removal (Vymazal and Kröpfelová 2009; Kyambadde et al. 2004). However, empirical exploitation of plants is a common practice. Availability, expected water quality, normal and extreme water depths, climate and latitude, maintenance requirements and project goals are amongst the variables that determine the selection of plant species for constructed wetlands (Stottmeister et al. 2003).

While there is a recognition that the improvement of water quality in treatment wetland applications is primarily due to microbial activity (Faulwetter et al. 2009; Kadlec and Wallace 2009), experience has shown that wetland systems with vegetation or macrophytes have a higher efficiency of water quality improvement than those without plants (Coleman et al. 2001; Tanner 2001; Brisson and Chazarenc 2009). The emphasis of constructed wetland technology to date has been on soft tissue emergent plants including *Cyperus papyrus*, *Phragmites*, *Typha* and *Schoenoplectus* (Kadlec and Wallace 2009; Okurut 2000). These are fast-growing species that have lower lignin contents and are adaptable to variable water depths. The productivity of emergent macrophytes is the highest amongst the aquatic plant communities in the tropics as well as in temperate regions. Emergent macrophytes are characterised by a photosynthetic aerial part above the water surface and a basal part rooted in the water substrate.

Emergent macrophytes find application in both surface and subsurface flow configurations of constructed wetlands. The significance of the plants used for wastewater purification has been emphasised by previous researchers (Brix 1997; Peterson and Teal 1996; Gersberg et al. 1983). Vymazal (2011) summarised the various roles played by emergent macrophytes in different configurations of constructed wetlands (Table 20.1).

Macrophyte plants, in addition to their site-specific roles (i.e. attenuation of light, water current and wind velocity, aesthetic appearance, etc.), are essential in the wetland treatment systems because they have properties that foster many wastewater treatment processes (Kyambadde 2005; Kadlec and Wallace 2009). Aquatic plants can absorb inorganic (nutrients, metals, etc.) and organic pollutants (aromatics, hydrocarbons, etc.) from wastewater and incorporate them into their own structure (Haberl et al. 2003), thus providing a storage and a release of nutrients through the plant growth cycle (NAS-NRC 1976; Shetty et al. 2005). They create favourable conditions for microbes that contribute to the processing of pollutants by influencing the oxygen supply to the water, providing attachment surfaces, providing carbon and electron donor via carbon content of litter and root exudates (Kadlec and Wallace 2009; Brix and Schierup 1989). Further, aquatic plants promote stable residual accretions in the wetland (Vymazal 2007; Greenway 2007). These residuals contain pollutants as part of their structure or in absorbed form and hence represent a burial process of contaminants (Kadlec and Wallace

Table 20.1 Major role of macrophytes in constructed treatment wetlands (Vymazal 2011)

Macrophyte property	Role in treatment process
Aerial plant tissue	Light attenuation – reduced growth of photosynthesis
	Influence of microclimate – insulation during winter
	Reduced wind velocity – reduced risk of resuspension
	Aesthetic-pleasing appearance of the system
	Storage of nutrients
Plant tissue in water	Filtering effect – filter out large debris
	Reduced current velocity – increased rate of sedimentation, reduced risk of resuspension
	Excretion of photosynthetic oxygen – increased aerobic degradation
	Uptake of nutrients
	Provision of surface for periphyton attachment
Roots and rhizomes in the sediment	Stabilising the sediment surface – less erosion
	Prevention of the medium clogging in vertical flow systems
	Provision of surface for bacterial growth
	Release of oxygen increases degradation (and nitrification)
	Uptake of nutrients
	Release of antibiotics, phytometallophores and phytochelatins

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2009). These facts have been exploited in constructed wetland systems which have been widely used during the past decades for the treatment of wastewater because of their good efficacy to improve water quality at low operational costs (Neralla et al. 2000; Vymazal 1999; Rousseau et al. 2004; Molle et al. 2005; Zurita et al. 2008; Perbangkhem and Polprasert 2010). The natural wetlands too have been shown to have potential as a sink and buffering site for organic and inorganic pollutants (Sekomo et al. 2010; Mannino et al. 2008; Buchberger and Shaw 1995; Muthuri and Jones 1997).

Wetland vegetation enhance evapotranspiration (and a corresponding increase in the hydraulic retention time) which can be explained by a net biomass productivity accompanied by transpiration (Kyambadde et al. 2005; Kansiime and Nalubega 1999). Emergent macrophyte vegetation tends to increase rates of water loss through evapotranspiration when compared to rates of evaporation from bodies of open water (Jones and Humphries 2002).

At present there is no clear evidence that treatment performance is superior or different between the common emergent wetland species used in treatment wetlands (IWA 2000; Zhu et al. 2010). Even so some soft tissue emergent macrophytes including *Phragmites* sp., *Schoenoplectus* sp., *Typha* sp. and *Carex* (true sedge) are well known for their potentials in constructed wetlands treating wastewater and faecal sludge, and their performances are well documented, especially for the high latitudes and temperate climate regions (Ciria et al. 2005; Stein et al. 2006;

Fennessy et al. 1994; Coleman et al. 2001). These macrophytes are, however, not found in all regions of the world and efforts are being made worldwide to select candidate macrophytes to be exploited locally in constructed wetlands (Brisson and Chazarenc 2009; Perbangkhem and Polprasert 2010; Azza et al. 2000; Huang et al. 2010; Yang et al. 2007).

20.3 *Cyperus papyrus* Macrophyte

20.3.1 History and Growth Habitat

Cyperus papyrus, commonly called papyrus or paper plant, is a member of the *Cyperaceae* sedge family, a group of plants closely related to grasses (Michael 1983). The *Cyperaceae* family has about 75 genera and more than 4,000 species, which are for a large part perennial rhizomateous herbs growing in moist places. *C. papyrus* has a long history of being harvested and has been used over millennia, such as for the manufacture of the first paper by the ancient Egyptians (Terer et al. 2012). It once grew wild throughout the Nile Valley (Egypt, Ethiopia) and can still be found in the swamps and marshes of Central, East and Southern Africa (El-Ghani et al. 2011; Chale 1987; van Dam et al. 2011; Boar et al. 1999). It was widely cultivated in Egypt for its many uses: boats, rope, food (boiled pith and rhizomes), sandals, boxes, mats, sails, blankets, cloth, mummy wrappings, firewood (dried rhizomes), medicine and building materials as well as writing materials (scrolls *papyri*) (Leach and Tait 2000). It is the largest of the sedges and a monocot that is native to riverbanks and mouths, lakeshores, floodplains and wet soil areas of North and tropical Africa. Outside Africa, it is thought to be native to the Hula Valley in Israel where it reaches its northernmost limits. It has been introduced and naturalised in the Mediterranean (Sicily, Malta), the USA (Florida) and India (Terer et al. 2012).

C. papyrus is the dominant species of many swamps in East and Central Africa and can be found growing in both lentic and lotic freshwater environments with stable hydrological regimes (permanently flooded). It cannot cope with rapid water level changes and water flow (Jones 1988; Jones and Muthuri 1985; Serag 2003; Kresovich et al. 1982). Due to its rhizomatic root structure, it can also be found floating with a mat-like root structure (up to 1.5 m thick) in open waters as deep as 3–4 m (Azza et al. 2000; Kansiime and Nalubega 1999; Thompson et al. 1979). As a member of the sedge family, it does not hold economic importance as a crop plant; nevertheless in some regions, it still finds application in weaving mats, baskets, screens and even sandals (van Dam et al. 2011; Osumba et al. 2010; Morrison et al. 2012).

A substantial number of sedges are weeds, invading crop fields in all climates of the world. Sedges do, however, have a considerable ecological importance. They are of extreme importance to primary production as well as an integral part of the hydrologic cycle (Saunders et al. 2007). Today, the most important uses of papyrus wetlands are those of ecological resources and services (Maclean et al. 2011; van Dam et al. 2007).

The *C. papyrus* wetland soils and plants may absorb or adsorb heavy metals, pathogens, inorganic forms of nitrogen, phosphorus, other nutrients and trace elements, and the rhizomes of the plant prevent soil erosion and trap polluted sediments from inflowing water. Consequently, *C. papyrus* has found application in both constructed and natural wetlands for water quality improvements. Thus, even in modern times papyrus may have an important role in cleaning up wastewater pollution from industrial, municipal and domestic sources as captured in the listed selection of studies in Table 20.2. Side-by-side investigations with unplanted controls show that the macrophyte *C. papyrus* has mostly a positive effect, i.e. supports higher treatment efficiency for the removal of organics (COD, BOD_5), faecal coliforms, heavy metals and nutrients such as nitrogen and phosphorus (Abira 2007; Okurut 2000; Kyambadde et al. 2005; Nyakang'o and van Bruggen 1999; Sekomo 2012).

In constructed wetland applications, *C. papyrus* has been found to establish well from rhizome fragment propagules and also to adapt well to wastewater conditions (Mburu et al. 2013; Abira 2007; Okurut 2000). This characteristic of vegetative reproduction via rhizomes and rapid recovery after damage to aboveground growth is shared by other effective invasive macrophytes such as *Phragmites* (Meyerson et al. 2000).

20.3.2 Cyperus papyrus *Morphology*

C. papyrus has its culm or stem (often triangular) growing to an average height of 3–5 m above ground and taking 6–9 months to mature (Gaudet 1977; Kresovich et al. 1982; Terer et al. 2012; Muthuri and Jones 1997). The culm has a large proportion of a spongy aerenchyma on its inside, and to a small extent, it is capable of photosynthesis (Okurut 2000). It is topped by characteristically large, spherical-shaped (finely dissected bracteoles), reproductive umbels (it bears flowers) that serve also as the main photosynthetic surface of the plant (Mnaya et al. 2007; Jones and Humphries 2002). The rhizomes and the roots together form a mat-like structure that is the base for swamp development. *C. papyrus* can grow well in the subtropical and tropical climate and is amongst the most productive plants of wetlands (Heers 2006; Kansiime et al. 2005; Perbangkhem and Polprasert 2010).

C. papyrus is considered to be unique due to its C_4 photosynthetic pathway in spite of the fact that it grows in a wetland ecosystem, which appears an unlikely habitat for C_4 species (Jones 1988, 1987; Jones and Humphries 2002; Saunders et al. 2007). Plants utilising the C_4 photosynthetic pathway show higher potential efficiencies in the use of intercepted radiation, water and nitrogen for the production of dry matter than do other photosynthetic types (Piedade et al. 1991). C_4 species are most numerous in tropical and warm, temperate semi-arid zones, where their

Table 20.2 Application and investigations of *Cyperus papyrus* macrophyte for water quality removal

Location	Set-up	Area	Type of (waste)water	Removal efficiency	Reference
Kenya	Experimental CW	3.2 × 1.2 × 0.8 m	Pulp and paper mill	[a]TN:75 %, [a]BOD: 90 %, [a]TSS: 81 %, [a]COD: 52 %, Phenols: 73–96 %	Abira (2007)
Uganda	Experimental CW	60 m^2	Urban sewage	BOD, NH_4^+-N, P: 68.6–86.5 %	Kyambadde et al. (2005)
Kenya (Kahawa swamp)	Natural wetland	3.7 ha	Domestic sewage	DO, NH_4^+-N, ortho-P: 77–85 %	Chale (1985)
Uganda (Nakivubo swamp)	Natural wetland	2.5 km^2	Urban sewage	[a] NH_4^+-N:89.4 %, [a]ortho-P: 80 %, [a]COD: 70 %	Kansiime et al. (2003)
Uganda	Experimental CW	320 m^2	Domestic sewage	TSS: 80 %, [a]coliforms: 4log units	Okurut (2000)
Congo (Upemba wetlands)	Rectangular transects, 2 × 10–20 m	250 m^2	Natural		Thompson et al. (1979)
Kenya	Operational CW	0.5 ha	Domestic sewage		Nyakang'o and van Bruggen (1999)
Thailand	Experimental CW	3 m^2	Domestic sewage		Perbangkhem and Polprasert (2010)
Kenya (lake Naivasha)	Quadrants 3 × 3 m (lake-)		Natural		Muthuri et al. (1989)
Tanzania (Rubondo Island)	Quadrants 0.5 × 0.25 m	1.41 km^2	Natural		Mnaya et al. (2007)
Kenya (Lake Naivasha)	Quadrants 0.5 × 0.5 m	150 km^2	Natural		Boar (2006)
Kenya (Lake Victoria shore)	Quadrants 2 × 2 m	60 km stretch	Natural		Osumba et al. (2010)
Rwanda (Nyabugogo wetland)	13 sampling sites	60 ha	Municipal/industrial (heavy metals)	Cd: 4.2, Cr: 45.8, Cu: 29.7, Pb: 56.1 All values in mg kg^{-1}	Sekomo et al. (2010)

(continued)

Table 20.2 (continued)

Location	Set-up	Area	Type of (waste)water	Removal efficiency	Reference
Uganda (Natete wetland)	Transects (325 m, 350 m long)	1 km^2	Municipal sewage	NH_4^+-N:21 %, NO_3^- -N: 98 %, TN: 45 %	Kanyiginya et al. (2010)
Egypt (Nile Delta)	50 sites (located by GPS)	2,250 km^2	Natural		El-Ghani et al. (2011)
Cameroon	Yard scale	1 m^2	Faecal sludge		Kengne et al. (2008)
USA	Microcosm	0.49×0.35 m	Synthetic sewage		Morgan et al. (2008)
China	Microcosm	0.26 m^2	Synthetic wastewater		Wang et al. (2008)

CW constructed wetland
[a]Maximum values

greater water-use efficiency appears to be a key selective advantage (Piedade et al. 1991). The C_4 photosynthetic pathway makes *C. papyrus* highly productive with dry weight biomass generation of up to 6.28 kg m^{-2} $years^{-1}$ (Terer et al. 2012).

Aerobic conditions in the roots and rhizomes of *C. papyrus* are maintained by oxygen transport from the atmosphere through the aerenchyma of the culms (Li and Jones 1995). Aerenchymous plant tissue is an important adaptation to flooding in wetland plants through which transport of gases to and from the roots through the vascular tissues of the plant above water and in contact with the atmosphere takes place (Singer et al. 1994). Li and Jones (1995) reported a diffusive oxygen transport between the rhizomes and the culms of 2.45 and 3.29 mol m^{-3} of oxygen at day- and night-time, respectively. This provides an aerated root zone and thus lowering the plant's reliance on external oxygen diffusion through water and soil (Kadlec and Wallace 2009).

In the tropical swamps *C. papyrus* establishment, growth and mortality occur concurrently through the year so that there is little temporal change in the standing crop (Muthuri et al. 1989). The culms can be divided into different age classes; some authors have used classification based on three age classes, namely, juvenile, with unopened umbels; mature, with opened green umbels; and senescent with more than half of the umbels brown (achlorophyllous) (Muthuri et al. 1989), while others have identified six age classes, namely, young elongated culm with closed umbel, elongated culm with umbel just opening, fully elongated culm and fully expanded umbel, fully elongated culm and fully expanded umbel but older, senescing culm (>10 % achlorophyllous) and dead culm (>80 % achlorophyllous) (Muthuri and Jones 1997). Culm density is controlled by density-dependent mortality (Thompson et al. 1979).

20.3.3 Cyperus papyrus *Biomass Productivity*

In both natural and constructed wetlands with *C. papyrus,* vegetative and reproductive parts above the ground level and their root systems comprise a substantial part of the wetland biomass (Fig. 20.1). Emergent macrophytes in swamps and marshes are amongst the most productive plant communities (Muthuri et al. 1989). *C. papyrus* vegetation is highly productive and under favourable temperatures, hydrological regime and nutrient availability estimates of aerial standing live biomass (including scale leaves, culm and umbel) often exceeding 5,000 g (dry weight) m^{-2} (Saunders et al. 2007).

The productivity of natural papyrus wetlands is found to be variable (Table 20.3) and controlled by different factors such as climate, nutrient availability and the prevailing general hydrological conditions (Okurut 2000). Differences in aerial biomass of papyrus in various sites have been attributed to prevailing climatic conditions. Some studies have noted a trend of an increase in standing biomass of papyrus swamps with increase in altitude. Nevertheless, this trend has not been

Fig. 20.1 Photos of the aboveground vegetative and reproductive parts of *Cyperus papyrus* in a constructed wetland at Juja, Kenya

found to hold true by all authors (Muthuri et al. 1989; Thompson et al. 1979; Mnaya et al. 2007). Unlike other emergent aquatic plants (Table 20.4), its high productivity rates and standing/harvestable biomass make *C. papyrus* have a high nutrient removal potential more so in wetlands receiving a high nutrient load. The harvesting of biomass presents a potential for biological nutrient removal (Kyambadde et al. 2005; Kansiime and Nalubega 1999).

Estimating biomass or primary productivity in tropical swamps, which have relatively stable biomass, requires measurements of population dynamics and the life cycle of individual shoots (Muthuri et al. 1989), unlike in the temperate ecosystems, where common methods of estimating primary productivity include measurements of peak biomass, maximum minus minimum biomass or methods which account for death and decomposition between harvests (Sala and Austin 2000; Muthuri et al. 1989).

20.3.3.1 Aboveground Biomass

The aerial organs of the *papyrus* (umbel, culm and scale leaves) contribute about 50 % of the total plant biomass (Thompson et al. 1979), in which the largest proportion is in culms (Muthuri et al. 1989). The high aerial biomass of the papyrus (Table 20.3) is unlike many other perennial emergent macrophytes such as *Typha latifolia* (890–2,500 g m^{-2}), *Scirpus validus* (2,355–2,650 g m^{-2}) and *Phragmites australis* (1,110–5,500 g m^{-2}) (Kadlec and Wallace 2009) that have a large proportion of their biomass in the form of roots and rhizomes (Muthuri et al. 1988). High aerial primary production indicates that less carbohydrate is assimilated in the rhizomes; hence, the living culms act as storage organs. This function is normally for the rhizome (Tanner 1996). Boar et al. (1999) established that biomass allocation to the various *C. papyrus* tissues is directly related to the fertility of the growing media such that least investment in roots and rhizome indicates plenty of nutrient supply. However, some studies have found that an

Table 20.3 Biomass production of *Cyperus papyrus* growing in different types of wetlands

Study/site	Biomass production (g dry mass m^{-2}) Below ground	Above ground	References
Pilot-scale FWS CW/Uganda	1,250	2,250	Kyambadde et al. (2005)
Natete wetland, Kampala, Uganda	1,288 ± 8.3	1,019 ± 13.8	Kanyiginya et al. (2010)
Man-made swamp/Kahawa swamp, Kenya	4,955[a]		Chale (1987)
Lake Naivasha, Kenya		3,245	Jones and Muthuri (1985)
Flooded river valley, Busoro, Rwanda		1,384	Jones and Muthuri (1985)
Nakivubo wetland (two sites), Uganda		883–1,156	Kansiime et al. (2003)
Pilot-scale-constructed wetland, Uganda		3,529–5,844	Kansiime et al. (2003)
Constructed wetland, Thailand	2,200–3,100[a]		Perbangkhem and Polprasert (2010)
Constructed wetland, Uganda	16,900–18,700[a]		Kansiime et al. (2005)
Natural wetland, Lake Naivasha, Kenya		2,731	Muthuri et al. (1989)
Natural wetland, Lake Naivasha, Kenya		4,652	Terer et al. (2012)
Rubondo Island, Lake Victoria, Tanzania	4,144 ± 452	5,789 ± 435	Mnaya et al. (2007)
Lake Naivasha, Kenya	6,950 ± 860[a]		Boar (2006)
Nakivubo wetland, Uganda	6,700[a]		Kansiime et al. (2007a)
Kirinya wetland, Uganda	7,200[a]		Kansiime et al. (2007a)
Nakivubo wetland, Uganda	1,158	2,480	Mugisha et al. (2007)
Kirinya wetland, Uganda	4,343	3,290	Mugisha et al. (2007)

FWS CW free water surface-constructed wetland
[a]Total biomass

important fraction of the plants' biomass is stored in the belowground stands of the papyrus (Kengne et al. 2008; Kanyiginya et al. 2010; Saunders et al. 2007).

20.3.3.2 Belowground Biomass

The belowground biomass of *C. papyrus* consists of an interlaced but permeable root mat with a rhizomatic structure (Kansiime and Nalubega 1999). Measurements

Table 20.4 Biomass production of other macrophytes growing in different types of wetlands

Macrophyte	Study/site	Biomass production (g dry mass m^{-2})		Reference
		Below ground	Above ground	
Colocasia esculenta	Nakivubo wetland, Uganda	1,236	2,024	Mugisha et al. (2007)
Colocasia esculenta	Kirinya wetland, Uganda	1,697	2,463	Mugisha et al. (2007)
Miscanthus violaceus	Nakivubo wetland, Uganda	870	1,190	Mugisha et al. (2007)
Miscanthus violaceus	Kirinya wetland, Uganda	1,470	1,680	Mugisha et al. (2007)
Phragmites mauritianus	Nakivubo wetland, Uganda	745	1,790	Mugisha et al. (2007)
Phragmites mauritianus	Kirinya wetland, Uganda	1,452	3,030	Mugisha et al. (2007)
Phragmites australis	Tidal salt marsh, N. America		727–3,663	Meyerson et al. (2000)
Phragmites australis	Freshwater marsh, N. America		980–2,642	Meyerson et al. (2000)

of rhizomes and root mass in the papyrus vegetation involve excavation to the maximum depth to which the roots are found (Muthuri et al. 1989). In natural swamps, the rooting mat has been estimated to contribute up to 30–52 % of the total biomass (Okurut 2000; Boar et al. 1999). The belowground biomass (i.e. the root and rhizomes) surface area provides attachment sites which are conducive for the proliferation of bacterial biomass. The roots and rhizomes influence the wastewater residence time, trapping and settling of suspended particles, surface area for pollutant adsorption, uptake, assimilation in plant tissues and oxygen for organic and inorganic matter oxidation in the rhizosphere (Kansiime and Nalubega 1999; Okurut 2000; Kyambadde et al. 2004). For example, the nature and density of the rooting biomass can greatly influence the extent of faecal bacteria removal via sedimentation and attachment processes. This influence was demonstrated in the studies of Kansiime and Nalubega (1999) in a natural wetland where faecal coliform counts were consistently higher in zones dominated by the *Miscanthidium violaceum* macrophyte, than in zones dominated by *C. papyrus*. The rooting mat of the former was tight and compact and thus had a reduced total surface area. In contrast, the papyrus mat is hollow and interwoven giving it a larger surface area for entrapment and attachment of faecal coliforms (Okurut 2000). Sekomo (2012) established that *C. papyrus* plants play an important role in metal retention. The *C. papyrus* root system was the most important part of the plant in heavy metal retention, followed by the umbel and finally the stem.

20.3.4 Nutrient Uptake and Storage

The removal of soluble inorganic nitrogen and phosphorus via absorption from either the water column or the sediment and storage in plant tissue is a direct mechanism of nutrient sequestration (Greenway 2007). Table 20.5 shows values for nutrient uptake of *C. papyrus* under different set-ups. The difference in the uptake rates may be attributed to nutrient availability under the experimental conditions and/or the growth phase of the macrophyte. A comparison of nutrient concentrations in plants, soil and water column in the Natete wetland (Kampala, Uganda) found that *C. papyrus* stored the highest amounts of nutrients as compared to soil and water (Kanyiginya et al. 2010). Plants take up nutrients as a requirement for their growth. These nutrients accumulate in plant parts which present an opportunity to remove excess nutrients from wetland systems through harvesting the aerial plant phytomass (Kansiime et al. 2007a). In this regard, plants with high rates of net primary productivity and higher nutrient uptake are preferred in wetlands subject to wastewater inputs (Kansiime et al. 2007a, b).

The nutrient elements essential for plant growth would be removed in proportion to their compositional ratios in the particular species (Boyd 1970). For *C. papyrus,* Chale (1987) found the nitrogen concentrations of the various plant organs were 4.8 % roots, 8.4 % rhizomes, 4.5 % scales, 4.8 % culms and 6.2 % umbels on dry weight basis. As compared to phosphorus, the concentrations were 0.09 % roots, 0.11 % rhizomes, 0.09 % scales, 0.10 % culms and 0.13 % umbels. A high content of nutrients is observed for the aerial biomass of papyrus, an indication of active translocation and storage of nutrients to parts of the plant where they are needed for primary growth, e.g. synthesis of amine acids and enzymes (Kyambadde et al. 2005; Muthuri and Jones 1997; Kansiime et al. 2007b). Significantly higher

Table 20.5 *Cyperus papyrus* nutrient uptake rates under varying experimental set-ups

Type of wastewater	P uptake (kg ha^{-1} days^{-1})	N uptake (kg ha^{-1} days^{-1})	Reference
Septic tank effluent (constructed wetland, Uganda)	0.24	7.1	Okurut (2000)
Natural wetland (Lake Naivasha)	0.06	1.18	Muthuri et al. (1989)
Municipal sewage (Nakivubo wetland)	0.21	1.3	Kansiime et al. (2003)
Natural wetland (Upemba swamps)	0.06	1.18	Thompson et al. (1979)
Domestic wastewater (constructed wetland)	0.14	3.01	Brix (1994)
Other macrophytes			
Phragmites australis (infiltration wetland)	0.22	2.14	Okurut (2000)
Eichhornia crassipes (diverse wastewaters)	0.2–2.0	1.6–6.6	Okurut (2000)

amounts of nutrients are sequestered in papyrus umbels and culms compared to roots/rhizomes portions (Kyambadde et al. 2005). Similar observations have been made by Mugisha et al. (2007) who established that photosynthetic organs of *C. papyrus* (culm and umbel) generally had a higher nutrient content than other organs (roots and rhizome) at the Nakivubo and Kirinya wetlands at the shores of Lake Victoria in Uganda. Nevertheless, nutrients in papyrus plants decrease with the age of the plant as the nutrients are translocated to the metabolically active juvenile plants for growth (Mugisha et al. 2007).

Okurut (2000) found nutrient removal from wastewater via plant uptake to show variability at different growth phases. The growth rate of *Cyperus papyrus* is the highest in juvenile plants and the lowest in mature plants, and the nitrogen uptake rate by *Cyperus papyrus* is the highest in juvenile plants and the lowest in mature plants. Uptake was correlated with the biomass yields exhibited in the different phases. The total nitrogen content was the highest in the juvenile plants and decreased with increasing age. This enables the plant to recycle nutrients from the old portions to new growth (Boyd 1970). Generally, (a) the rate of nutrient uptake by macrophytes is limited by its growth rate and the concentration of nutrients within the plant tissue, and (b) nutrient storage is dependent on the plant tissue nutrient concentration and potential for biomass accumulation (Greenway 2007).

20.4 Wastewater Treatment with *Cyperus papyrus*

Cyperus papyrus plays an important role in the water quality enhancement, the effects of which can be readily observed in terms of dissolved oxygen (DO), pH and redox potential of their surroundings and the attenuation of pollutant parameter profiles from influent to effluent (Huang et al. 2010; Okurut 2000). For constructed wetlands to be effective in water pollution control, they must function as a "pollutant" sink for organics, sediments, nutrients and metals, i.e. these pollutants must be transformed, degraded or removed from the wastewater and stored within the wetland either in the sediment or the plants. Although there is still debate about the relative importance of macrophytes versus microbes in nutrient removal, plant biomass still accounts for substantial removal and storage of nitrogen and phosphorus (Brix 1997; IWA 2000).

Macrophytes can contribute directly through uptake (nutrients and heavy metals), sedimentation, adsorption or phytovolatilisation or indirectly to pollutant removal in constructed wetlands. Indirect processes are related to biofilm growth around roots, evapotranspiration and the pumping of oxygen towards the rhizosphere that changes the redox conditions (Imfeld et al. 2009; Carvalho et al. 2012; Kadlec and Wallace 2009). Some of these mechanisms are addressed in the sections below.

20.4.1 Root Oxygen Release into the Rhizosphere

Papyrus-dominated wetlands like all other natural wetlands are characterised by low dissolved oxygen concentrations (Okurut 2000). The main reason for this state is that surface aeration and photosynthetic oxygen transfer mechanisms are poor or non-existent due to the dense plant canopy. On the other hand, oxygen leakage to the rhizosphere is important in constructed wetlands with subsurface flow for aerobic degradation of oxygen-consuming substances and nitrification (Brix 1994). The photosynthetic characteristics of wetland species can affect their ability to provide oxygen, and this ultimately influences their disposal efficiencies.

The peak photosynthetic quantum efficiency, i.e. the amount of CO_2 that is fixed or the amount of O_2 that is released via assimilation when the photosynthetic apparatus absorbs one photon (Huang et al. 2010) for *C. papyrus*, has been reported to range between 26 and 40 μmol CO_2 m^{-2} s^{-1} (Jones 1987, 1988; Saunders and Kalff 2001). In their work on plant photosynthesis and its influence on removal efficiencies in constructed wetlands, Huang et al. (2010) published the photosynthetic rates of five wetland plants, *Phragmites, Ipomoea, Canna, Camellia* and *Dracaena,* at light saturation. These ranged between 11.6 and 31.32 μmol CO_2 m^{-2} s^{-1}. *C. papyrus* presents a comparable potential for oxygen production via photosynthesis. Kansiime and Nalubega (1999) estimated oxygen release rates of 0.017 g m^{-2} $days^{-1}$ by C. *papyrus* plants. The oxygen released is available for microbiota within the rhizosphere.

20.4.2 Surface for Microorganism's Attachment

In natural and constructed wetlands, macrophyte root structures provide microbial attachment sites. In an experimental microcosm set-up, Gagnon et al. (2007) found that microbes were present on substrates and roots as an attached biofilm and abundance was correlated to root surface throughout depth. Indeed planted wastewater treatment systems outperform unplanted ones, mainly because plants stimulate belowground microbial populations (Gagnon et al. 2007). Plant species root morphology and development seem to be key factors influencing microbial–plant interactions. Kyambadde et al. (2004) measured a higher root surface and microbial density in a constructed wetland planted with *C. papyrus* (average root surface area 208.6 cm^2) compared to *Miscanthidium violaceum* (average root surface area 72.2 cm^2). *C. papyrus* and *Miscanthidium violaceum* differed in their root recruitment rate and root number in a microcosm-constructed wetland. The root recruitment rate per constructed wetland unit was 77 and 32 roots per week for *C. papyrus* and *Miscanthidium violaceum,* respectively, and *C. papyrus* had more adventitious roots and larger root surface area than *Miscanthidium violaceum* (Kyambadde et al. 2004). Further, *C. papyrus* seems to promote greater nitrogen removal efficiencies, through nitrification and denitrification rates of bacteria associated with it roots (Morgan et al. 2008).

20.4.3 *Evapotranspiration*

The average daily water vapour flux from the papyrus vegetation through canopy evapotranspiration in a wetland located near Jinja (Uganda) on the Northern shore of Lake Victoria was approximated by Saunders et al. (2007) as 4.75 kg H_2O m^{-2} days^{-1} (=4.75 mm days^{-1}), which was approximately 25 % higher than water loss through evaporation from open water (approximated as 3.6 kg H_2O m^2 days^{-1}). Jones and Muthuri (1985) reported an evapotranspiration rate of 12.5 mm days^{-1} at the fringing papyrus swamp on Lake Naivasha, while Kyambadde et al. (2005) reported 24.5 ± 0.6 mm days^{-1} for a subsurface horizontal flow wetland in Kampala (Uganda). Evapotranspiration rates vary sharply since they depend on numerous factors influencing the ecosystem's prevailing microclimate, as listed by Kadlec and Wallace (2009). For example, common reed transpiration rates oscillate between 4.7 and 12.4 mm days^{-1} depending on meteorological conditions (Holcová et al. 2009). Evapotranspiration (ET) by plants can significantly affect the hydrological balance of treatment wetlands. The water lost through ET concentrates pollutants within the wetland, while the volume reduction results in longer hydraulic retention times (Kadlec and Wallace 2009). For low-loaded systems or systems with longer retention times, such evapotranspiration rates can exceed the influent wastewater flow, leading to a zero discharge.

20.4.4 Cyperus papyrus *Harvesting and Regeneration Potential*

In order to achieve a permanent nutrient removal from wetland systems, *C. papyrus* harvesting is encouraged, but this requires careful timing (Kiwango and Wolanski 2008). Total nitrogen in aerial biomass of *C. papyrus* decreases from the juvenile plants to older plants (Mugisha et al. 2007). Hence, to minimise internal nutrient cycling and eventual export of the nutrients from wetland systems, sustainable harvesting of aerial biomass at different growth stages can be used as a strategy to reduce nutrients, especially in wastewater treatment wetlands. The regeneration potential of *C. papyrus,* i.e. the inherent capacity for natural regrowth and replenishment, on a site after a disturbance has been found to be highly reliable (Osumba et al. 2010). However, overharvesting (within less than one 6-month growing season) of *C. papyrus* can reduce this regeneration potential leading to weak spatial connectivity, papyrus stand fragmentation and increased landscape patchiness in natural wetlands (Osumba et al. 2010). Modelling studies of papyrus wetlands by van Dam et al. (2007) have proposed a harvesting rate between 10 and 30 % of the total biomass per year. At higher harvesting rates, nutrient uptake and retention by papyrus does not increase proportionally because of reduction in plant biomass, leading to lower uptake (van Dam et al. 2007). Muthuri et al. (1988) established a ceiling aerial biomass of 2,731 g m^{-2} after 6 months, at a previously harvested section of a swamp at Lake Naivasha (Kenya), while for the undisturbed sections of the swamp, an aerial biomass of 3,602 g m^{-2} was recorded. Water levels after harvesting are thought to affect biomass yield. Osumba et al. (2010) found that flooded sites give the least regenerated biomass yields.

20.5 Conclusion

This literature survey reveals that the macrophyte *C. papyrus* has found application in constructed wetlands for remediating a variety of pollutants in wastewater from different sources. The majority of the application of the *C. papyrus* macrophyte in constructed wetlands is found in the developing tropical countries, where papyrus is occurring locally. The macrophyte possesses a robust morphology and metabolism, and it is easy to establish and manage, thus making constructed wetlands incorporating *C. papyrus* wetland vegetation a promising wastewater treatment option for wider application. The production and harvesting of vegetation biomass from these treatment wetlands can provide a permanent route for the removal of nutrients, with economic benefits for communities that engage in the trade of papyrus products.

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