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Wetland Technology

Practical Information on the Design and Application of Treatment Wetlands

Edited by Günter Langergraber, Gabriela Dotro, Jaime Nivala, Anacleto Rizzo and Otto R. Stein

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4.7 BIOMASS PRODUCTION

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4.7.1 Perspectives for energy production from TW biomass

Traditional wastewater treatment plants are significant consumers of energy. Nevertheless, they can produce biogas in the sludge digestion process which is mainly used for heating the facilities at the treatment plant or is converted to electricity; however the net energy balance is still negative in the majority of cases (McCarty *et al*., 2011). Compared to traditional wastewater treatment plants, TW, owing to their design and operation, have lower energy demand per se.

The main objective of TW is to treat wastewater and thus protect natural ecosystems from pollution; however, TW have numerous additional functions, among which biomass production is getting increased attention. Biomass can be used for energy production, which is a growing area of research as a response to the global energy crisis and the effects on climate change. In this aspect, TW offer additional value compared to conventional cultivation of energy crops due to reuse of wastewater for production of biomass, i.e., the need for application of mineral fertilizers and irrigation to produce energy crops is significantly reduced or even eliminated.

TW are cost-efficient and often economically outcompete conventional systems which can become even more obvious when using the produced biomass as an energy source. Since TW are mostly used for decentralized wastewater treatment, centralized energy production of the produced biomass is a challenge due to transport and sustainability. Decentralized stations or individual systems for heat energy production are often not economically feasible in developed countries; the return on investment in the equipment for production and storage of wood chip and pellets is longer than a lifespan of TW. However, the situation is the opposite in developing countries where significant parts of the population rely on wood for cooking, which can be substituted with biomass from TW (Avellán & Gremillion, 2019).

There is a fast-growing number of TW for wastewater treatment, both in developed and developing countries, resulting in thousands of operating TW in the world. However, not many TW are used for energy production, even though there is great potential: Liu *et al.* (2012) found that TW even have greater greenhouse gas reduction than conventional systems for production of biofuel in a complete life-cycle. Despite this, currently in the majority of operating TW worldwide, the produced biomass is composted or combusted as waste.

4.7.2 Sources and production of bioenergy within or post TW

Biomass for energy production can be grown within the TW or by fertigation of energy crops with the TW's effluent. Pellets or woodchip can be produced already from the plants that are usually grown within the TW, e.g., *Phragmites* sp., *Typha* spp., *Phalaris* sp., *Cyperus* sp. etc. or from willow wood in case of willow systems. The pellets and woodchip can be directly used for heating in appropriate furnaces or wood stoves.

Willow systems are a type of TW that is planted with willows (see Chapter 5.10 Willow systems). Willows are energy crops commonly used in short rotation coppices where they can produce around 10 t DM ha^{-1} per year with the application of artificial fertilizers, while in willow systems, owing to high nutrient and water availability, biomass production can triple (Istenič *et al.*, 2018). According to Gregersen and Brix (2001) the amount of nutrients that enter the system with wastewater is approximately the same as the amount of nutrients in willow biomass, i.e., the composition of the wastewater corresponds to the willows' nutrient requirements (Börjesson & Berndes, 2006).

According to Liu *et al.* (2012) wetlands can produce 1.1 to 184 $MJ/m^2/yr$. Energy production of TW is directly linked to biomass production (Table 4.4), which depends on nutrient availability or mass loading rate. Besides this, climate, latitude and elevation have to be considered. Because the primary function of TW is wastewater treatment, most TW remain at a low biomass productivity level. The latter can be scientifically increased by selecting productive plant species, optimizing the flow pattern and taking an advantage of using waste nutrients and water (Liu *et al.*, 2012); moreover, harvesting and regrowth after it also affect the biomass yield. Designing a wetland to increase biomass production will also have a significant impact on evapotranspiration and thus on the amount of discharge from the system. In arid areas water availability might be a limiting factor for biomass production.

Phragmites australis is the most commonly used plant in TWs worldwide and its energy production is similar to other wetland plants (Table 4.4). Higher energy production per m^2 can be reached by *Cyperus papyrus* or by willow systems and the highest by *Arundo donax*, which is currently not often used in TW.

The energy produced from biomass grown in TW has to be compared against the energy input needed for TW operation. According to Liu *et al.* (2012), the net energy balance for vertical flow TW with pulse loading is positive, meaning that there is more energy produced than needed for operation. Moreover, the net energy balance is also higher compared to some other systems for production of energy crops (e.g., soybean, corn, microalgae).

TW can also contribute to production of bioenergy through reuse of treated wastewater for energy crops irrigation and fertilization. To achieve high productivity particularly in summer crops irrigation is generally necessary; in this context, treated wastewater presents an important water source. Post-wetland production of energy crops combines different advantages. Water fertilizing properties decrease the demand for

Table 4.4 Biomass production and energy yield for different plant species growing in TWs.

Type of Plant	Biomass Production in TW	Combustion Energy Yield	Energy Production	Methane Production
	kg DM m^{-2}/yr	MJ/kg · DM	MJ m^{-2}/yr	L/kg · DM
Phragmites spp.	1.9 ± 1.3[1] 3.3 ± 1.1[8]	18[1]	34 ± 24* 44 ± 31[4]	108–236[1]
Typha spp.	1.6 ± 0.9[1]	18[1]	29 ± 16* 37 ± 36[4]	NA
Arundo donax	6.1 ± 4.5[1] 2.1–4.9[7]	18[1] 17–24[7]	109 ± 81* 132 ± 34[4]	297[1]
Cyperus papyrus	3.6 ± 2.5[1]	18[1]	64 ± 44* 48 ± 6[4]	NA
Miscanthus sp.	0.6–3.8[7]	16–19[7]	22[4]	152[5]
Phalaris sp.	1.3 ± 0.5[8]	NA	23 ± 11[4]	185[9]
Salix spp.	3.3 ± 0.9[2]	19.8[3]	64 ± 18*	172[6]

*Calculation from production and combustion data: [1]Avellán and Gremillion (2019); [2]Istenič *et al.* (2018); [3]Keoleian and Volk (2005); [4]Liu *et al.* (2012); [5]Yang and Li (2014); [6]Triolo *et al.* (2012); [7]Ge *et al.* (2016); [8]Vymazal and Kröpfelová, (2005); [9]Lakaniemi *et al.* (2011).

Table 4.5 Biomass production and energy yield for different plant species irrigated with TW effluent (Barbagallo *et al*., 2014; Molari *et al*., 2014).

Type of plant	Biomass Yield	Combustion Energy yield	Energy Production
	kg DM m^{-2}/yr	MJ/kg · DM	MJ m^{-2}/yr
Arundo donax	2.6–7.9	21	55–166
Miscanthus giganteus	0.5–4.5	18	9–81

synthetic fertilizers and contribute to the reduction of nutrients loading in rivers; this practice increases the available agricultural water resources and it may lower treatment costs.

When using TW effluent for energy crops irrigation, the TW type can be simplified, i.e., to enable degradation of organic matter producing an outflow rich in nutrients which can be used for fertigation of energy crops such as herbaceous plant species (*Arundo spp., Myschantus spp.,* etc.) and short rotation coppices (willow, poplar, acacia).

Several research programmes were carried out in Italy (Barbagallo *et al*., 2014; Molari *et al*., 2014) highlighting the potential in the use of TW effluents for irrigation in order to reach high herbaceous biomass production. The perennial species, such as *Arundo donax* (L.) and *Miscanthus* × *giganteus* Greef et Deu., proved to be the most productive and with high heating values (Table 4.5). The two species are declared as "poor" crops due to the low economic value of their biomass; therefore, the use of conventional sources of water and chemical fertilizer is not feasible. However, where wastewater is readily available at low cost, *A. donax* and *M. giganteus* can be a very interesting option for wastewater reuse with benefits for the environment and farm income.

4.7.3 Design objectives

Wastewater with high concentrations of ammonium, sulphides, salts and metals may inhibit nutrient uptake and consequently the growth of wetland plants. Therefore, it is essential to know the quality of wastewater to be treated in order to select appropriate wetland plant species, which are known to have different capacity for nutrient uptake, different preferences for nitrogen forms and have evolved various adaptive mechanisms that protect them against the toxicity of inorganic substances.

Wastewaters with high concentrations of nutrients stimulate the growth of wetland plants that can accumulate, preferably on the above-ground tissues, more nutrients than that are needed for growth (so called 'luxury uptake'); however, the timing for biomass harvesting can influence the removal of nutrients from the TW:

- A single annual harvest performed in late summer, before the translocation of nutrients to the root system, allows removal of the maximum amount of nutrients from the TW. However, high concentrations of nutrients in the biomass can cause corrosive effects on the combustion plant. Furthermore, low concentrations of nutrients and carbohydrates in the roots could result in reduced plant regrowth in the next year. If the biomass is used for biogas production, a single harvest in late summer or two harvests at early growth stages have the advantages of lower lignin contents with better digestion kinetics and consequently higher methane yield.
- A single annual harvest performed in late autumn implies a reduction of biomass yield, due to loss of leaves, but ash and moisture contents decrease, creating a higher biomass quality for direct combustion.

Many metals such as Cu, Fe, Mn, Ni and Zn are involved in numerous plants' metabolic processes as constituents of enzymes and other proteins. However, they can become toxic if their concentration is higher than a specific critical point, as they can lead to a range of interactions at the cellular and molecular levels. In general, wetland plants are not hyper-accumulators; they store metals in below-ground tissues (Batty & Younger, 2004). Consequently, the health risks of above-ground wetland biomass as a solid fuel appear to be comparable to more traditional fuel sources.

In contrast, the low bulk density of biomass produced by herbaceous wetland plants can cause an incomplete combustion with a consequently poor air quality from cooking fumes and an increase of health risks (WHO, 2016).

4.7.4 Specific considerations during design, for construction and operation

There are some key parameters that should be considered in the design and construction phase of a TW for biomass production:

- In order to produce more biomass for energy purposes, the amount of nutrients in the supplied water has to be adjusted to the nutrient needs of the target crop. This leads to the situation when a complete elimination of nutrients in TW is not desired, therefore TW can be simplified or reduced in area.
- Appropriate TW technology has to be selected: FWS wetlands have lower energy production potential compared with subsurface flow TW owing to aquatic plants having lower biomass production per area unit compared with mesophytes.
- Appropriate plant species have to be selected in order to produce more biomass for energy purposes.
- Additional harvesting or thinning of the stand has to be considered in order to increase biomass production.
- From the perspective of plant regrowth and longevity, harvesting should not occur until plants are sufficiently mature that rhizomes have been resupplied with nutrients and carbohydrates.
- Appropriate ash disposal has to be considered, namely ash content of wetland biomass (usually 5–10% of dry mass) is higher compared with wood ($<1\%$) (Avellán & Gremillion, 2019).

Water quality standards across the world are being re-written to promote healthier ecosystems, ensure safe potable water sources, increased biodiversity, and enhanced ecological functions. Treatment wetlands are used for treating a variety of pollutant waters, including municipal wastewater, agricultural and urban runoff, industrial effluents, and combined sewer overflows, among others. Treatment wetlands are particularly well-suited for sustainable water management because they can cope with variable influent loads, can be constructed of local materials, have low operations and maintenance requirements compared to other treatment technologies, and they can provide additional ecosystem services. The technology has been successfully implemented in both developed and developing countries.

The first IWA Scientific and Technical Report (STR) on Wetland Technology was published in 2000. With the exponential development of the technology since then, the generation of a new STR was facilitated by the IWA Task Group on Mainstreaming Wetland Technology. This STR was conceptualized and written by leading experts in the field. The new report presents the latest technology applications within an innovative planning framework of multi-purpose wetland design. It also includes practical design information collected from over twenty years of experience from practitioners and academics, covering experiments at laboratory and pilot-scale up to full-scale applications.

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