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Cultivation of energy crops in constructed wetlands for wastewater treatment: an overview

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Abstract. The need for sustainable, clean, and secure energy sources is a current issue for all nations. All kinds of vegetal biomass can be used as energy-source or as raw material for biofuel production, but some species are commonly classified as energy crops. This work evaluates the energy potential of 35 species of energy crops when produced in constructed wetlands (CW). Producing energy crops in CW is a route to link wastewater treatment to energy production, avoiding the abstraction of freshwater for crop irrigation, and simultaneously avoiding the use of arable land. However, for most of the energy crops, there are no data available in the literature about biomass productivity in CWs. Although 20 of the 35 crops have been tested as CW vegetation, the biomass productivity in CWs was only found for 13 species. Reported biomass productivity in CW is similar to or even higher than the productivity reported for conventional production, but most reported data is for pilot-scale CW, which points to the need for future work in full-scale systems. From the combination of biomass productivity and the biomass calorific value, *Arundo donax*, *Miscanthus x giganteus*, *Cynodon dactylon*, *Phragmites australis*, and *Typha latifolia* show higher ranges up to 3064 MJ/ha year for *Arundo donax*. Future works on CW design can be focused on the potential of using energy crops as vegetation.

1. Introduction

Sustainable, clean, and market-secure energy is a current hot topic for all nations. Although thermal and photovoltaic direct capture of solar energy and indirect solar-driven sources of renewable electricity such as wind and dams are attaining market share, biomass-derived biofuels consist in a solution for many applications where electrification may be difficult or expensive (1).
Biomass is usually referred to as plants or other photosynthetic organisms such as algae (2,3). Almost all kinds of plant biomass can be used directly as a heat source by combustion or converted to a range of biofuels such as bioethanol, biodiesel, and biogas (4). Energy crops are species in which energy valorization is traditional or easier such as maize (*Zea mays*), sorghum (*Sorghum spp*.), sugarcane (*Saccharum officinarum*), switchgrass (*Panicum virgatum*), and willow (*Salix viminalis*), among others (5–7). Although energy crops represent a relevant alternative to non-renewable fuels, their cultivation requires land, fresh water, and fertilizers, competes with the food and feed chains, and can cause negative impacts on greenhouse gas emissions and biodiversity (8–10).
Plants are an essential component of constructed wetlands (CW). CW are engineered systems that use the treatment mechanisms of natural wetlands to eco-efficiently treat wastewater (11,12). CW vegetation is usually named macrophytes and can be rooted or floating species depending on the type of wetland design. The plants contribute directly to the uptake of nutrients and other water pollutants,

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and indirectly through the fixation of biofilms, transfer of oxygen and pH regulation, providing conditions for pollutants assimilation and conversion by microorganisms, and conferring thermal isolation, preventing clogging, allowing wildlife habitat, and contributing to aesthetics of CW (13–15). To avoid the back release of nutrients into the system at the end of the plant's growing season the wetlands vegetation must be harvested, which can provide biomass for bioenergy and other uses (16,17). This approach can be a contribution of CW to the water-energy nexus: using CW to produce vegetal biomass for bioenergy applications avoids simultaneously the need for arable land, fertilizers, and freshwater.
Although the literature on bioenergy is vast the potential of using CWs as a source of biomass for biofuels production is scarcely explored. Therefore, the purpose of this work consists in evaluating the energy potential of producing crops in CWs. To attain that goal, the review work of Laurent et al. (5) on the productivity of energy crops under conventional cultivation was used as the basis for the identification of the main plant species cultivated for energy purposes. Then, the energy potential was computed from available data in the literature on crop productivity in CWs and on its energy production by combustion.

2. Methods

The present work was conducted in four steps:

- A first survey of the literature to obtain references to productivity in CWs of the species identified in the work of Laurent et al. (5);
- Selection of species whose productivity in CWs is reported;
- A second survey of the literature to gather data of calorific value expressed as Higher Heating Value (HHV, MJ/kg) for the selected species;
- Computation of the energy potential of each specie, consisting of the product of the productivity (ton/ha year) by the HHV to obtain the calorific potential of cultivation in CWs (MJ/ha year).

The lower and higher reported figures of biomass productivity and calorific value were used to obtain a low-high range of calorific potential of crops cultivation in CWs.

3. Results and discussion

The work of Laurent et al. (5) reports 35 species of energy crops, giving data on biomass productivity in land conventional production. The *Saccharum spp*. was not considered in the present work because the cited work also reports values of *S. arundinaceum* e *S. officinarum*.
Figure 1 shows the relative use of the 35 species in CWs, from the first survey. The common reed (*Phragmites australis*) and cattail (*Typha latifolia*) are the most common wetland plants. *Arundo donax*, *Phalaris arundinacia*, and *Pennisetum purpureum* are less common wetland plants. Those results are in line with several review works on CW's plants (18–22). The remaining energy crops are rarely tested as CW vegetation. Moreover, any work on CWs was identified for 15 of the reported energy crops. Those first results point to future perspectives for research on the evaluation of non-conventional CWs vegetation focusing on its valorization as energy raw material.
Although 20 of the 35 crops have been tested as CW vegetation, the biomass productivity in CWs was only found for 13 species (Table 1). Figure 2 presents the minimum and maximum plant biomass productivity in CW retrieved from the surveyed literature. The figure also shows the range of biomass productivity reported by Laurent et al. (5).
Although several species have been evaluated in full-scale CWs, most reported productivity data reports to pilot-scale and even lab-scale experiments. From figure 2 it can be observed that the productivity in CWs is higher than the production in soil, but the lack of results obtained in full-scale CWs, and from a long-time operation, prevents concluding that CW's productivity in real operation can be so high. However, there can be concluded that the productivity in CWs is not below the productivity in soil, which is a positive result.

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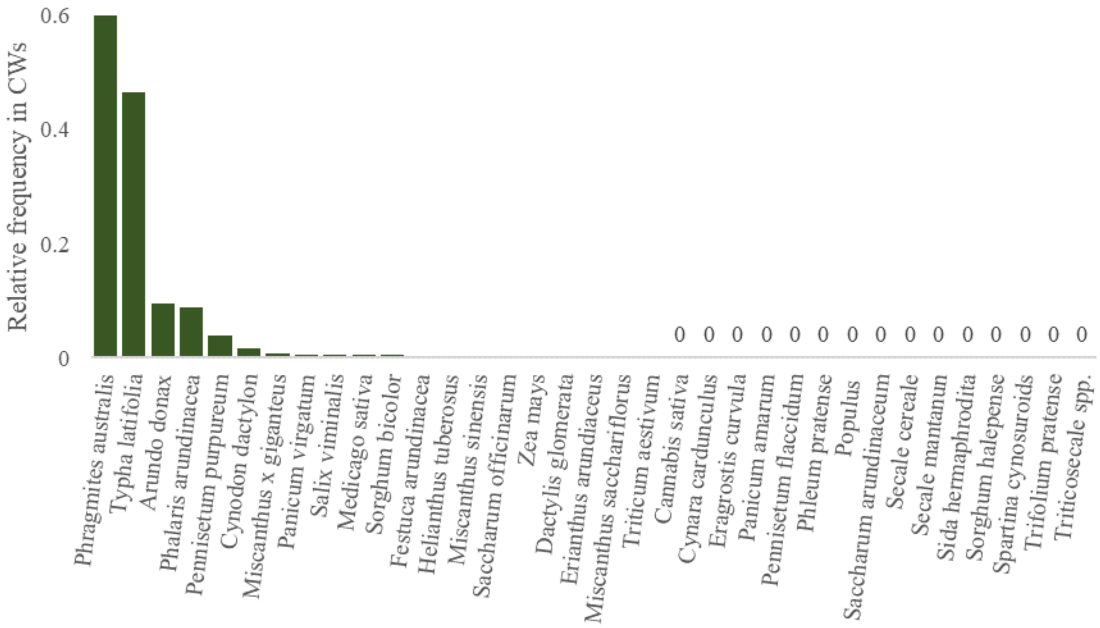

Figure 1. Relative frequency of the surveyed works that refer to the use of energy crops as constructed wetland vegetation. The *Phragmites australis* frequency corresponds to the unit but the y-axis range is reduced to show the lower frequency results. The zeros identify the species for which no records of use in CWs were found.

Table 1. Biomass productivity in CWs and reported Higher Heating Value[a].

Specie	CW scale	Biomass productivity (ton/ha year)	HHV (MJ/kg)
Arundo donax	Pilot, Full	6.7 to 159.6 (23,24)	17.68 to 19.2 (25)
Cynodon dactylon	Pilot	7.5 to 86.3 (26,27)	17.96 to 19.18 (28,29)
Helianthus tuberosus	Pilot	5.9 (30)	14.93 to 17.6 (31,32)
Miscanthus x giganteus	Pilot	110.4 (23)	17 to 19.5 (32,33)
Panicum virgatum	Lab	0.1 (34)	16.5 to 19.2 (32,33)
Pennisetum purpureum	Pilot	8.1 to 25.0 (26,35)	18.11 to 18.55 (36,37)
Phalaris arundinacea	Full	3.4 to 22.3 (38,39)	16.6 to 18.7 (40)
Phragmites australis	Pilot, Full	13.6 to 83.1 (23,30)	18.49 to 18.72 (41,42)
Saccharum officinarum	Pilot	8.4 to 27.2 (43,44)	17.83 to 18.77 (45,46)
Salix viminales	Pilot, Full	4.8 to 16.4 (47)	16.13 to 19.26 (47)
Sorghum bicolor	Lab, Pilot	1.3 to 23.6 (34,48)	15.58 to 18.4 (48,49)
Typha latifolia	Pilot	20.2 to 41.8 (50,51)	17.02 to 20.5 (52)
Zea mays	Pilot	10 (53)	17.68 to 19.02 (54,55)

[a] Minimum and maximum values reported in the surveyed literature are presented.

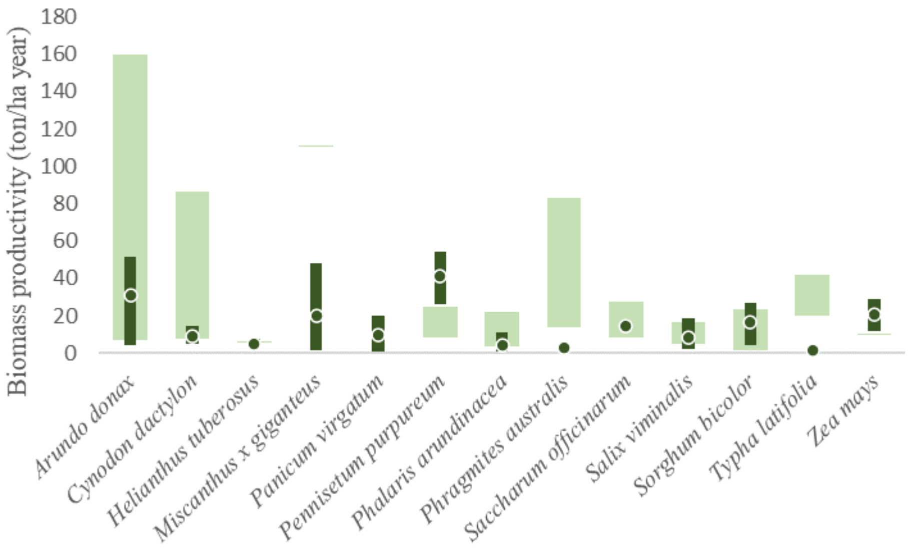

Figure 2. Biomass productivity. The light and large bars present the range of productivity in CWs. The dark and narrow bars present the range of productivity in soil, as reported by Laurent et al. (5). The dots represent the average value in soil.

Figure 3 presents the estimated energy potential for the 13 energy crops when produced in CWs. Although the results may be affected by the uncertainty and scarcity of biomass productivity data in CWs, *Arundo donax*, *Miscanthus x giganteus*, *Cynodon dactylon*, *Phragmithes australis*, and *Typha latifolia* show the higher energy potential by hectare and year. All these species are very common or common vegetation of CWs. The energy potential of *Saccharum officinarum* and *Sorghum bicolor*, two uncommon CW's vegetation, is lower than the 4 most energy-productive species but is similar to some common CWs plants, such as *Pennisetum purpureum*, *Phalaris arundinacea*, and *Salix viminalis*.

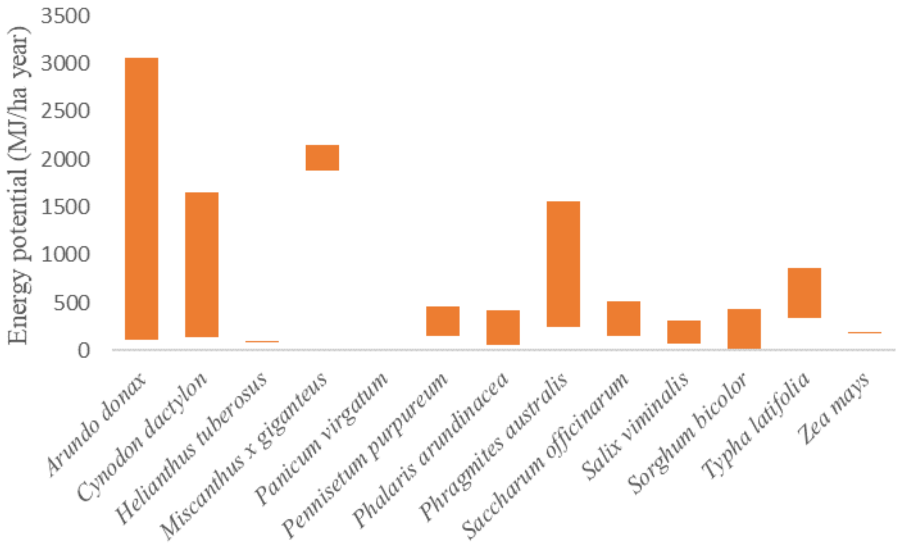

Figure 3. Estimated energy productivity of energy crops cultivated in CWs treating wastewater.

The energy productivity of energy crops as CW's vegetation was estimated on a simple calorific value basis. However, crop biomass can be converted into different types of biofuels by biochemical or thermochemical processes, such as bioethanol, biodiesel, and biohydrogen, among others. As an example, the most common CW plant (*Phragmites australis*) has already been studied as a raw material for the production of bioethanol by aerobic fermentation after hydrolysis [56-58], biogas by anaerobic digestion [59,60], biohydrogen by dark fermentation [61], syngas by gasification [62], and bio-oils by pyrolysis [63]. This evidence represents an opportunity to develop a framework for the future use of constructed wetlands as a source for a broad matrix of biofuels.
Although the main goal of constructed wetlands is the treatment of wastewater, the sustainability of this green technology can be improved through the bioenergy valorisation of the plant biomass produced. However, more research efforts should be made to select operational conditions that allow using energy crops as vegetation without compromising the phytoremediation objective of CW's plants. At this point, the five species with the greatest potential are common CW vegetation, but other energy crops may also have effective phytoremediation capabilities. In the present overview, the productivity or even the capability as a phytoremediation plant was not found for several energy crops. Thus, further work can be carried out to assess the potential of energy crops as the vegetation of constructed wetlands, assessing their ability to remove pollutants from wastewater and to grow in the aquatic environment of constructed wetlands.

4. Conclusions

The use of CW vegetation for energy production makes this wastewater treatment technology more sustainable because it avoids the use of arable land and freshwater for irrigation. Thus, avoiding the main disadvantages of producing energy crops.
In this overview work, the energy potential of cultivating energy crops in CWs was evaluated through available data on biomass productivity and the calorific values of energy crops. A total of 35 species of energy crops were considered, but data on biomass productivity in CWs was found for only 13 species.
Although the results may be affected by the uncertainty and scarcity of biomass productivity data in CWs, *Arundo donax*, *Miscanthus x giganteus*, *Cynodon dactylon*, *Phragmites australis*, and *Typha latifolia* show a higher energy potential by hectare and year, from 118 to 3064 MJ/ha year for *Arundo donax*, a less common CW's vegetation. For comparison, the evaluated energy-productivity of *Phragmites australis*, the most common CW vegetation, ranged from 251 to 1556 MJ/ha year.
Future work on the evaluation of energy crops as CW's vegetation could be a way to increase the sustainability of CWs, and develop a framework to connect wastewater treatment and recovery with bioenergy production, alleviating the pressure on freshwater extraction and land usage for energy purposes. The perspective of valorising the vegetation of CWs can be intensified as a research goal but also making part of CW's set of design criteria.

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