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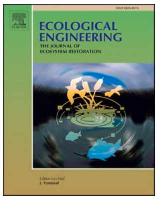

Short communication

Bioenergy routes for valorizing constructed wetland vegetation: An overview

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ABSTRACT

Valorizing constructed wetlands vegetation into biofuels can be a way to contribute to mitigating the increasing energy demand, avoiding the use of arable land, freshwater, and fertilizers consumption, while simultaneously treating wastewater with eco-friendly technology. This work shortly overviews the main genera of wetland plants and the main routes of vegetal biomass conversion into biofuels including biochemical and thermochemical processes, and through a cross-search, in the Scopus database, the research intensity in bioenergy application for each genus was assessed. A total of 283 genera of wetland plants were identified and classified into five groups, from very common to very rare genera. The very common group includes 10 genera and contributes to 62% of the literature hits, while the 147 genera classified as very rare contribute to only 3% of the hits. Concerning the bioenergy applications, four genera stand out from the remaining. The plants of the genus *Sorghum* are the most referred to in bioenergy applications, followed by the genera *Brassica*, *Miscanthus*, and *Saccharum*. *Miscanthus* is a less common wetland plant, while the other genera are rarely applied in constructed wetlands. The relevance of bioenergy routes depends on the plants' group. For common wetland plants, the most relevant applications are biogas production, followed by bio-ethanol production, and pyrolysis processing. As a recommendation for future research works the genera with high energy potential should be evaluated as wetland vegetation, and it is recommended that the goal to recover wetland vegetation for bioenergy applications be viewed as an integral step of the design and implementation of constructed wetlands facilities.

1. Introduction

Is well known that our society is strongly dependent on energy, and the replacement of fossil fuels with renewable energy sources is a mandatory goal for sustainable development. Renewable energy includes solar-driven sources: thermal and photovoltaic, wind, tides, waves and dams energy collectors, and biomass produced by autotrophic organisms (Li et al., 2022a). In addition, the earth is a source of heat that although not renewable is long-term (geothermal power).

Biomass consists of living or dead organisms of all kinds but is commonly referred to as plants or other photosynthetic organisms such as bacteria and algae which can be used as a source of biomolecules or energy (Ahmed et al., 2022; Siddiki et al., 2022). Plant biomass is an ancestral source of energy as heat, being nowadays a promising source of biofuels with almost a neutral balance on the emission of carbon dioxide and other gases contributing to climate change. 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, biogas, and bio-hydrogen, among other biofuels (Liu et al., 2022).

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 (Laurent et al., 2015; Margaritopoulou et al., 2016; Oleszek et al., 2019). 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 have negative impacts on greenhouse gases emissions and biodiversity (Fritsche et al., 2010; Knápek et al., 2021; Paschalidou et al., 2018). Reducing freshwater consumption through the optimization of irrigation systems (Scardigno, 2020), managing the crop and product selection (Zheng et al., 2022), and using marginal lands (Blanco-Canqui, 2016; Khanna et al., 2021), can be ways to mitigate those issues but are not of straightforward implementation.

Plants are an essential component of constructed wetlands (CW). CW

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are engineered systems that use the treatment mechanisms of natural wetlands to efficiently treat wastewater (Mader et al., 2022; Vymazal, 2022). CW vegetation is usually named macrophytes and can be rooted or floating species depending on the type of wetland (free water surface or subsurface flow) and substrate. The plants contribute directly to the uptake of nutrients and other water pollutants, 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 (Jesus et al., 2018; Kulshreshtha et al., 2022; Sandoval et al., 2019). 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 (Avellan et al., 2017; Avellán and Gremillion, 2019). This approach can be a huge 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 constructed wetlands as a source of biomass is scarcely explored. The purpose of this work consists in uncovering that potential by matchmaking the most studied wetland vegetation with the most studied plants for bioenergy applications. Besides CWs' vegetation generally show low energy density compared to woody and conventional energy crops (Ambaye et al., 2021), this water-saving and land-saving combination represents a win-win strategy, thus treating wastewater by an eco-efficient and green technology, and simultaneously producing biomass in non-arable lands. Moreover, some woody species and energy crops can be used as CWs' vegetation with any or low prejudicial effect on the wastewater treatment capabilities (Grebenshchykova et al., 2020). The present work aims to motivate the intensification of future studies on the energy valorization of CWs vegetation, making this part of the guidelines for CW design.

The number of published works on the production of energy and fuels from biomass is very large. Moreover, biomass is a broad concept. In the context of this work, the designation of biomass refers to the whole, parts, or wastes of plants, which consists of the main raw materials for biofuel production. Consequently, there are several reviews on technologies for bioenergy valorization of vegetal biomass. Three main groups of technological routes can be devised: (1) direct combustion; and (2) thermochemical or (3) biochemical conversion to solid, liquid, and gaseous biofuels. Thermochemical technologies are based on complex biomass polymers and other organic molecules conversion into simpler molecules including biofuels and other compounds via heat-based reactions. Biochemical technologies convert biomass to simpler molecules based on the action of microorganisms or enzymes.

The main technologies consist in:

- Aerobic fermentation to obtain ethanol also referred to as bioethanol, and other alcohols (**E**) (Melendez et al., 2022);
- Anaerobic fermentation to obtain methane-rich gases also referred to as biogas, and sometimes simply by biomethane (**B**) (Govarthanan et al., 2022);
- Transesterification or hydrogenation of vegetable oils to obtain biodiesel (**D**) (Alsultan et al., 2021);
- Dark fermentation and other biological routes to obtain hydrogen are also referred to as bio-hydrogen (**H**) (Agyekum et al., 2022);
- Direct combustion of biomass or mechanical-derived products such as pellets and other agglomerates (**C**) (Marreiro et al., 2021);
- Gasification to obtain mainly gaseous products (syngas), and solids and liquids as by-products (**G**) (Maitlo et al., 2022);
- Pyrolysis to obtain mainly liquid products (bio-oil), and solids and gases as by-products (**P**) Anyalewechi, Okieimen, & Kusuma, 2021) (Amenaghawon et al., 2021);
- Torrefaction for conversion of biomass into dense and dried solids, usually designated as bio-coal (**T**) (Sarker et al., 2021);
- Hydrothermal liquefaction with or without catalysts to obtain mainly liquid products, also usually designated as bio-oils (**L**) (Li et al., 2022b).

The letter within parenthesis in the above list will be used in the present work to identify the technologies for biomass conversion.

Hydrogen production is a particular case because it can be obtained by all thermochemical processes, namely by gasification (Ji and Wang, 2021; Lepage et al., 2021), but also by pyrolysis (Fahmy et al., 2020). In this work, only the production of Hydrogen by fermentation of biomass is referenced to technology "**H**".

Pretreatment of biomass by biological, chemical, and thermal processes, or a combination of these processes, is a common approach to fractionating the biomass, liberating cellulose, hemicellulose, lignin, and other organic constituents (Zhao et al., 2022), as the first step to turn possible or more efficient the conversion to biofuels. Sometimes, these processes, mainly the biological ones, are also designated as biomass liquefaction (Deshavath et al., 2021). However, in this work, the letter "**L**" is reserved for Hydrothermal liquefaction, in which the main product is a liquid fraction (bio-oil) comprising a complex mixture of organic compounds.

There is no known review work on the general potential for energy production from wetland plants. However, some published works present data on the potential valorization of wetland plants for bioenergy purposes. There is no known example of large-scale use of plant biomass obtained from constructed wetlands for bioenergy applications. Though, Liu et al. (2012) carried out work with 12 plots of five pilot-scale constructed wetlands and reviewed 52 works on CWs. The authors performed a life-cycle assessment to estimate the energy balance and greenhouse gas emissions for the CWs. Although the estimated productivity varies over a wide range, the authors concluded that the bioenergy yield can be improved by optimizing the CWs water flow, and by the selection of appropriate plants. Although the authors identified *Arundo donax* as a primary candidate, they also stated that *Phragmites australis*, *Typha* spp., and *Miscanthus* spp. are also potential species. Avellan et al. (2017), and Avellán and Gremillion (2019), reviewed the literature on biomass production by constructed wetlands, crossing the results with the potential to obtain bioenergy from the plants. These works present the potential for energy production by direct combustion, and the potential to obtain biogas. In the first work, the authors observed that the selection of the plants as constructed wetland vegetation seems to be not based on their potential to produce energy. *Typha* and *Phragmites* are commonly used and show high potential as energy sources. *Scirpus, Juncus,* and *Eleocharis* are also common but show low energy potential. On the other hand, *Arundo donax* is less frequently used as wetland biomass but has high energy potential. In the second work, four species were selected for comparison: *Arundo donax*, *Cyperus papyrus*, *Phragmites australis,* and *Typha angustifolia*. *A. donax* and *C. papyrus* shows the highest biomass productivity. Kaur et al. (2018) made a review on potential applications of aquatic weeds as feedstock for biofuel production. The authors postulate that plants can be harvested from aquatic ecosystems including constructed wetlands but not exclusively. Main goal consists in aquatic ecosystems protection from the spread of invasive plants. Potential use of some species as biofuel raw material was reviewed, such as *Eichhornia crassipes*, Duckweed, a group of aquatic plants from 5 genera (*Lemna*, *Landoltia*, *Spirodela*, *Wolffia*, and *Wolfiella*), *Azolla* sp., *Salvinia molesta*, *Typha* sp., and *Pistia stratiotes*. Bioethanol and biohydrogen are identified as major applications of the identified aquatic weeds.

This study aims to present the first overview of the bioenergy valorization of plants grown in constructed wetlands. All biofuel conversion routes are included, not just the traditional ones. In addition to the direct combustion of wetland biomass and to its conversion into biogas, bioethanol or biodiesel, research has been carried out on conversion to biohydrogen and on thermochemical processes such as gasification, pyrolysis, hydrothermal liquefaction, and torrefaction. The goals of the present study are: (i) Assess the reported use of plants as constructed wetland vegetation, including less used genera; (ii) Assess the intensity of research on the application of each genera in each route of bioenergy valorization; (iii) Identify the main bioenergy applications of the more commonly used wetland plants; (iv) Provide and overview of the research on less commonly used wetland genera that have a high intensity of research in bioenergy applications.

2. Materials and Methods

To determine the intensity of research on the use of different genera of plants in constructed wetlands and in bioenergy applications, literature published until 2021 was surveyed using the following search strategy:

1. Published reviews focusing on treatment wetlands or constructed wetlands were assessed to identify the genera of plants used in these wastewater treatment technologies;
2. The Scopus database was searched using each genus identified combined with “constructed wetland” or “treatment wetland”, in the title-abstract-keywords”;
3. The citation section of the documents identified in step 2 was surveyed to identify additional genera, and step 2 repeated for each of these genera;
4. Each document identified was assessed for inclusion in the present work by checking in the material and methods section that the plant genus was used as constructed wetland vegetation;
5. A second search of the Scopus database was carried out using each genus identified and each keyword set related to bioenergy applications (“anaerobic fermentation” or “bioethanol” or “bio-ethanol”; “anaerobic digestion” or “biogas” or “biomethane”; “biodiesel” or “bio-diesel”; “biohydrogen” or “bio-hydrogen”; “combustion”; “gasification”; “pyrolysis”; “torrefaction”; “liquefaction”);
6. Each document identified was assessed for inclusion in the present overview by checking that the plant genus was used for bioenergy valorization.

All documents identified in the literature search were assessed for relevance as described in steps 4 and 6. A significant fraction of reports on bioenergy applications were not included in the present overview because the reference to bioenergy production is only generic, or the matched keywords pertain only to analytical methods. From the reports validated for inclusion, the intensity of research on each plant genus was calculated by adding the number of reports studying the use of the genus in constructed wetlands and in bioenergy valorization. Some works studied more than one plant or technology, resulting in a total sum greater than the number of documents. Using descriptive statistics, research intensity on constructed wetlands and bioenergy applications was compared for each genus, between genera, and for different types of bioenergy applications.

3. Results

3.1. Recent reviews on constructed wetland plants

In a first step, recent review works were analyzed to identify the usual genera of plants used as CW’s vegetation. Table 1 presents some published reviews. Combining the 8 review works cited in Table 1, 118 different genera and 280 different species were identified. The most referred genera are *Typha*, *Phragmites,* and *Scirpus*.

Reported works on the screening and evaluation of the potential of plant species for phytoremediation are also common in the literature. For example, Schück and Greger (2020) carried out experimental work to evaluate the capacity of 34 species (24 genera) to remove heavy metals from water, and Grebenshchykova et al. (2020) compared the removal efficiency of pollutants by five woody species (from the genera *Salix*, *Sambucus*, *Myrica,* and *Acer*) with the removal efficiency of common wetland plants, such as *Typha*, *Phragmites,* and *Phalaris*.

Table 1
Review works on plants used in constructed wetlands.

Reference	Number of genera and species	Most observed genera
(Vymazal, 2011)	52 genera, 82 species	*Phragmites, Typha, Scirpus.*
(Vymazal, 2013)	60 genera, 141 species	*Typha, Scirpus, Phragmites, Juncus, Eleocharis.*
(Bhatia and Goyal, 2014)	24 genera, 44 species	*Phragmites, Typha, Spartina, Scirpus, Juncus.*
(Jesus et al., 2018)	22 genera, 29 species	*Typha, Phragmites.*
(Sandoval et al., 2019)	33 genera, 48 species	*Canna, Iris, Heliconia, Zantedeschia.*
(Sanjrani et al., 2020)	42 genera, 65 species	*Canna, Iris, Heliconia, Zantedeschia, Phragmites, Typha.*
(Kataki et al., 2021)	35 genera, 42 species	*Phragmites, Typha, Cyperus, Canna, Pennisetum, Pistia, Arundo, Glyceria, Iris, Vetiveria.*
(Varma et al., 2021)	23 genera, 36 species	*Typha, Scirpus, Phragmites.*

3.2. Research intensity on the use of the different genera of plants in constructed wetlands

After steps 1 to 4, the search carried out identified 283 genera of plants. The relevance of each genus was sorted by the number of hits in the retrieved documents, after validation. 10 genera counted more than 100 hits each, corresponding to nearly 62% of all hits, and were named in this work as “very common”. The “common” group includes 26 genera that obtained at least 25 hits, corresponding to nearly 21% of all hits. The “less common” group includes 31 genera that scored at least 10 hits. The “rare” group includes 69 genera that obtained more than 2 hits. The last group named “very rare” contains 147 genera, which is more than half of the total number of identified genera. Two genera of algae are included (*Chara*, in the less common group, and *Cladophora*, in the rare group). Considering the number of hits, the five groups ranked in the direct order of relevance, with the large “very rare” group counting only for 3% of the total hits. Plants from the genera *Phragmites* and *Typha* are the most common. The results are in line with the literature referred to in section 3.1.

3.3. Research intensity on the bioenergy application of plants used in constructed wetlands

Table 2 summarizes the results published on the evaluation of the energy potential of biomass harvested from treatment or constructed wetlands, highlighting the type of bioenergy application. Most works focus on the direct combustion of biomass, or bioethanol and biogas production. There is no review work on the remaining six types of bioenergy valorization routes.

As described in section 2 a search was conducted for each identified plant genus to obtain the number of works describing the application for the 9 kinds of bioenergy routes according to the classification in section 1. The genera with more hits are presented in Fig. 1, and Table 3. Although all 10 very common genera are shown in Table 3, only 4 genera have a significant number of hits for bioenergy: *Phragmites*, *Typha*, *Eichhornia*, and *Lemna*. Five common genera of wetland plants are heavily referenced (*Arundo*, *Phalaris*, *Salix*, *Pennisetum*, and *Spartina*), as well as 3 less common, 5 rare, and 4 very rare genera. Fig. 1 shows the apparent relevance of bioenergy applications (y-axis) against the apparent relevance of wetland plants (x-axis). Four genera show high popularity for bioenergy applications: *Sorghum*, *Brassica*, *Miscanthus*, and *Saccharum*. Among them, *Miscanthus* is a less common

Table 2
Summary of works on the bioenergy potential of plants used in constructed wetlands.

Reference	Bioenergy application	Studied species
(Odhiambo et al., 2009)	Biogas	*Bambusa siamensis (Thyrsostachys siamensis), Phragmites australis*
(Suda et al., 2009)	Bioethanol	*Typha* spp.
(Wang et al., 2011)	Direct combustion (calorific value)	*Bolboschoenus planiculmis, Colocasia esculenta, Cyperus malaccensis, Eichhornia crassipes, Eleocharis dulcis, Hedychium coronarium, Hygrophila pogonocalyx, Ipomoea aquatica, Leersia hexandra, Ludwigia x taiwanensis, Marsilea crenata, Miscanthus floridulus, Murdannia keisak, Nymphaea tetragona, Phragmites communis, Polygonum hydropiper, Schoenoplectus mucronatus, Typha orientalis, Zizania latifolia*
(Liu et al., 2012)	Bioethanol, biogas, and direct combustion (estimative)	*Arundo donax, Canna indica, Miscanthus sinensis, Phragmites australis, Saccharum arundinaceum*
(Bonanno et al., 2013)	Direct combustion	*Arundo donax, Phragmites australis*
(Cohen et al., 2013)	Biogas (co-digestion)	*Azolla filiculoides, Hydrocotyle ranunculoides, Lemna* spp.*, Spirodela* spp.
(Soda et al., 2013)	Bioethanol	*Eichhornia* spp.*, Pistia* spp.
(Jiang et al., 2014)	Biogas	*Acorus calamus, Canna indica, Colocasia tonoimo, Hydrocotyle vulgaris, Pontederia cordata, Thalia dealbata, Typha orientalis*
(Zhao et al., 2014)	Direct combustion (calorific value)	*Arundo donax, Canna indica, Cyperus alternifolius, Phragmites* spp.*, Thalia dealbata, Vetiveria zizanioides*
(He et al., 2015)	Bioethanol	*Alisma* sp.*, Aspidistra elatior, Canna indica, Cyperus alternifolius, Eichhornia crassipes, Hedychium coronarium, Iris pseudacorus, Nephrolepis auriculata, Phragmites australis, Thalia dealbata, Typha angustata, Typha latifolia, Veronica undulata, Zantedeschia aethiopica*
(Gizińska-Górna et al., 2016)	Direct combustion (calorific value) and Biogas	*Helianthus tuberosus, Miscanthus x giganteus, Phragmites australis, Salix viminalis*
(Liu et al., 2019)	Bioethanol (estimative)	*Arundo donax, Canna indica, Cyperus papyrus, Glyceria maxima, Phalaris arundinacea, Phragmites australis, Typha latifolia*
(Lin et al., 2020)	Bioethanol	*Eupatorium adenophorum, Fargesia spathacea, Juncus effusus, Phragmites australis, Thalia dealbata*
(Fahim et al., 2021)	Bioethanol	*Canna indica, Ipomoea aquatica, Iris pseudacorus, Oryza sativa*

wetland plant, and the remaining three are rarely employed as wetland vegetation.

Globally, the most cited bioenergy applications are bioethanol and other alcohol production, biogas and biomethane, and biodiesel, by this order (Fig. 2). Within each group of plant popularity as constructed wetland vegetation, the distribution is different. The use of very common plants is dominated by biogas production, followed by bioethanol production, and pyrolysis processing. Biogas production is relevant for common and less common plants, as its use for bioethanol production, and direct combustion. Besides the production of bioethanol and biogas, biodiesel production was identified as a common application of rare and very rare genera. The use of wetland vegetation biomass for biohydrogen production, torrefaction, or liquefaction is less referred to.

4. Discussion

This work aimed to overview the potential application of wetland vegetation for bioenergy applications. Future detailed work may be carried out to review each kind of bioenergy application for each kind of wetland vegetation, eventually done at the specie level. It is not the objective of this work to review the literature to evaluate the productivity of biomass in CW or the bioenergetic productivity of the harvested plant biomass. However, the results obtained can be useful to make a first overview, since previous review works are scarce, and focused on a few bioenergy applications such as bioethanol, biodiesel, biogas, and direct combustion. One goal of this work is the evaluation of the research interest also in less-common applications of wetland biomass such as biohydrogen production, gasification, pyrolysis, liquefaction, and torrefaction.

Based on the analysis of the results presented in section 3, it can be observed that for the most common wetland plants (very common and common according to the designation used in this work), the literature retrieved mostly focuses on research in biogas, bioethanol, direct combustion, and pyrolysis, by this order. Liquefaction, biodiesel, biohydrogen, gasification, and torrefaction are fewer common applications.

Although energy crops such as maize show higher biogas production than common wetland vegetation, several works present wetland plants as greener and more sustainable alternatives. Biogas production yield depends on the growth conditions, harvesting season, moisture content, and the operating conditions of the anaerobic digestion. Considering the results of this work, 6 genera of wetland plants show high research intensity on their use as feed stock for biogas production. Ordering by the reported average biogas yield potential, in Ndm^3/kg, it follows; *Lemna* average yield is 421 (Calicioglu et al., 2019; Kaur et al., 2019); *Typha* is 388 (Eller et al., 2020; Hartung et al., 2020); *Phalaris* is 336 (Czubaszek et al., 2021; Laasasenaho et al., 2020); *Arundo* is 313 (Eller et al., 2020; Piccitto et al., 2022); *Phragmites* is 305 (Eller et al., 2020; Scherzinger et al., 2021); and *Eichhornia* is 100 (Kist et al., 2020; Sarto et al., 2019).

Bioethanol production from lignocellulosic biomass requires pretreatment, saccharification, and fermentation steps. Overall yield depends on several parameters and operative conditions. Despites the difficulty to compare results, the reported average potential of bioethanol production in g/kg for the 4 common wetland plants that showed higher research intensity is similar: 282 for *Arundo* and *Typha* (Goli and Hameeda, 2021; Paramasivan et al., 2021; Sidana et al., 2022); 245 for *Eichhornia* (Sunwoo et al., 2019); and 179 for *Lemna* (Calicioglu et al., 2019; Kaur et al., 2019).

Direct combustion is the third most reported bioenergy route for valorizing common wetland plants. Usually, the higher heating value (HHV), in MJ/kg is reported. Three wetland plants received show the highest research intensity according to the results of the present work. By order of reported values, the average HHV of *Phragmites* is 18.6 (Bernal et al., 2021; Demko et al., 2017), 18.4 for *Arundo* (Cano-Ruiz et al., 2020), and 17.7 for *Phalaris* (Usťak et al., 2019).

Finally, pyrolysis processing is commonly referred to as 4 common wetland plants. Pyrolysis results in a mixture of solid, liquid, and gaseous products. Biochar, the solid phase, can be used as fuel but its main applications are as a soil amendment or adsorption media. The liquid phase, bio-oil, is mainly applied as fuel. Ordering by the mass fraction of bio-oil production, the highest average values of nearly 47% are reported for *Eichhornia* (Ilo et al., 2022; Wauton and Ogbeide, 2022). Bio-oil mass fractions of 39%, 35%, and 32%, were reported respectively for *Arundo* (Saynik and Moholkar, 2021), *Phragmites* (Aysu, 2014), and *Lemna* (Djandja et al., 2021).

As already referred to in section 3, 4 genera of uncommon wetland plants are intensely studied for bioenergy applications: *Sorghum*, *Brassica*, *Miscanthus*, and *Saccharum*.

Sorghum spp. are rarely referred to as wetland vegetation, and only in lab-scale experiments: Zhou et al. (2011) studied the growth of *Sorghum sudanense*, and its phytoremediation potential, proposing this species as

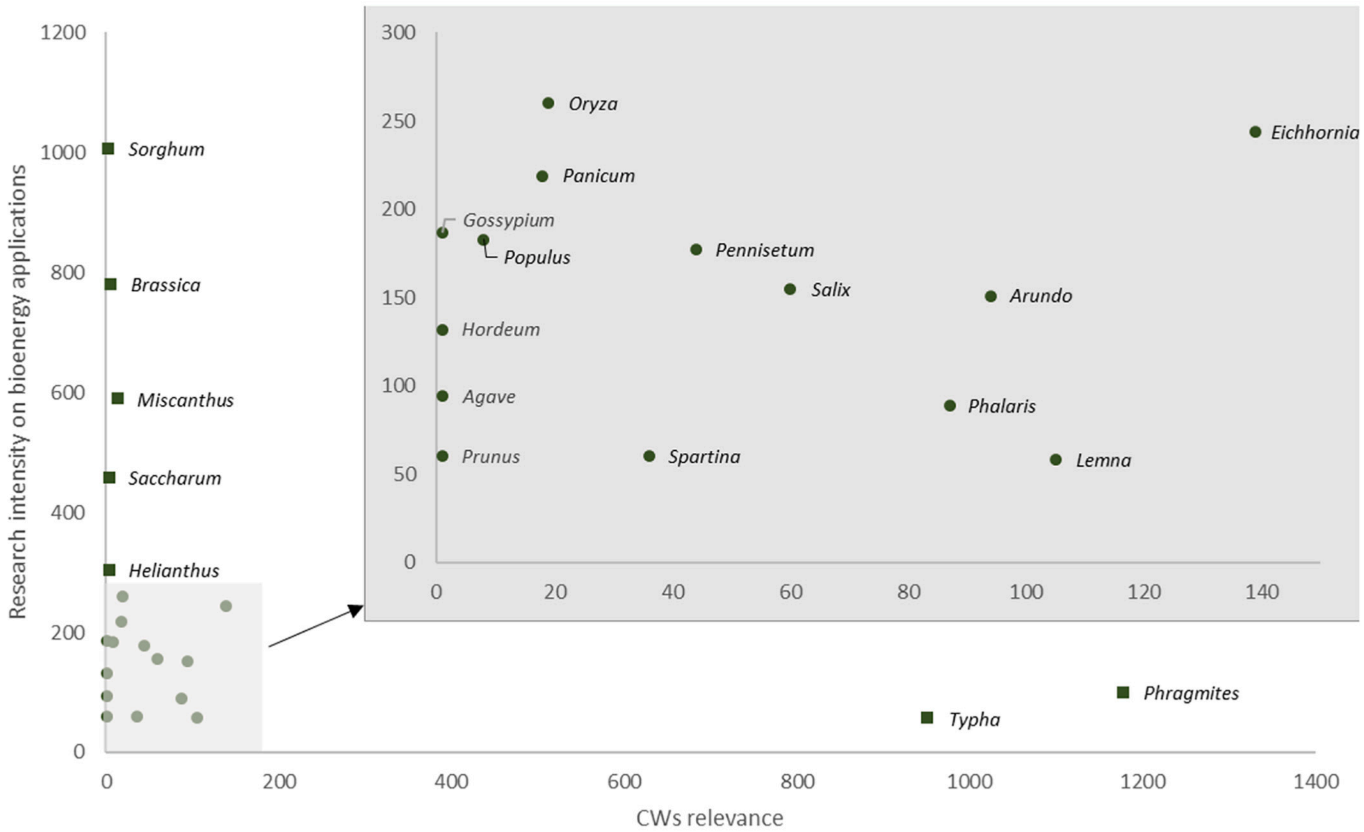

Fig. 1. Research intensity of plant's genera for bioenergy applications against the research intensity in CW applications, according to the number of hits. The inserted upper-right figure shows the details in the lower value of the axis.

Table 3
Distribution by bioenergy applications for very common and bioenergy-relevant plants.

CW plants' relevance	Wetland plant			Type of bioenergy application (#)								
	Genus	Main specie (*)	Family	E	B	D	H	C	G	P	T	L
Very common	*Phragmites*	*Phragmites australis*	*Poaceae*	10	33		4	26	2	17	4	3
	Typha	*Typha latifolia*	*Typhaceae*	18	21		2	4		6	1	4
	Canna		*Cannaceae*	2	2			1		2		
	Cyperus	*Cyperus alternifolius*	*Cyperaceae*	6	1	6		3		1		
	Iris	*Iris pseudacorus*	*Iridaceae*	2	1	1						
	Schoenoplectus	*Schoenoplectus californicus*	*Cyperaceae*		1							
	Juncus	*Juncus effusus*	*Juncaceae*	3	3			2				1
	Scirpus		*Cyperaceae*		1							
	Eichhornia	*Eichhornia crassipes*	*Pontederiaceae*	62	105	9	10	16	2	32	1	7
	Lemna	*Lemna minor*	*Araceae*	25	12	1	2	1	2	7	1	7
Common	*Arundo*	*Arundo donax*	*Poaceae*	37	44	13	4	23	3	23	2	2
	Phalaris	*Phalaris arundinacea*	*Poaceae*	11	28			46	1	3		
	Salix		*Salicaceae*	28	19			56	13	28	3	8
	Pennisetum	*Pennisetum purpureum*	*Poaceae*	57	79	1	3	16	2	17	1	1
	Spartina		*Poaceae*	9	31		1	1	5	8		5
Less common	*Oryza*	*Oryza sativa*	*Poaceae*	90	92	8	8	32	12	11	5	2
	Panicum	*Panicum repens*	*Poaceae*	91	35	3	2	35	24	24	3	2
	Miscanthus		*Poaceae*	119	84	3	4	173	57	122	16	11
Rare	*Populus*		*Salicaceae*	69	11	6		53	7	25	3	9
	Brassica		*Brassicaceae*	33	23	684	1	9	3	25	1	1
	Helianthus		*Asteraceae*	26	42	187	1	4	17	25	1	
	Saccharum		*Poaceae*	322	61		15	17	12	27	3	1
	Sorghum	*Sorghum bicolor*	*Poaceae*	496	188	64	17	68	28	91	6	48
Very rare	*Gossypium*	*Gossypium hirsutum*	*Malvaceae*	20	14	70	4	14	5	41	13	6
	Hordeum		*Poaceae*	64	28	1	6	13	3	10	2	5
	Agave		*Asparagaceae*	45	29	3	11	5		1		
	Prunus		*Rosaceae*	2	2	45		10	1			

[*] Main specie if identifiable.

[#] Number of published works.

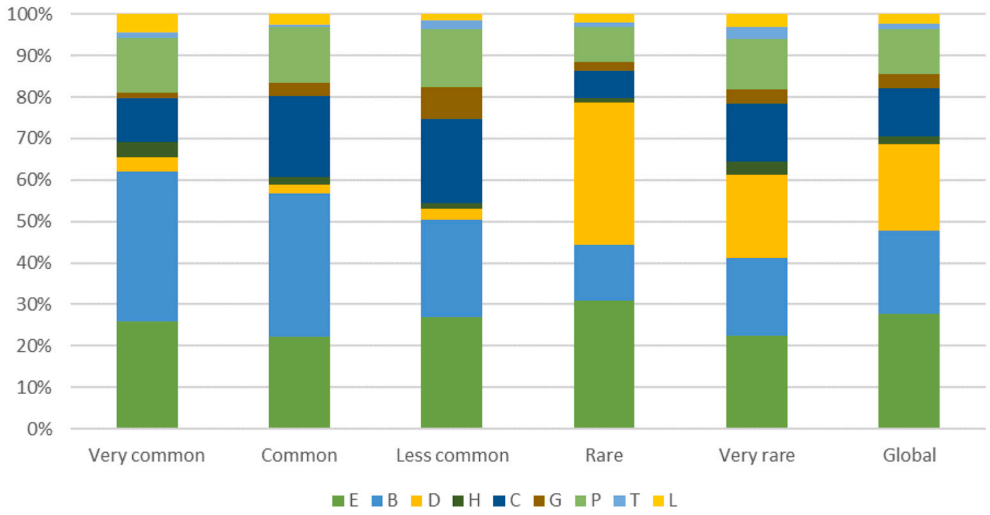

Fig. 2. Relative research intensity for each kind of bioenergy application in each group according to the classification from very common to very rare wetland vegetation: (E) Bioethanol; (B) Biogas; (D) Biodiesel; (H) Biohydrogen; (C) Combustion; (G) Gasification; (P) Pyrolysis; (T) Torrefaction; (L) Liquefaction.

constructed wetland vegetation; Zhu et al. (2017) studied the use of *Sorghum bicolor* as the vegetation of lab-scale constructed wetlands filled with gravel, sand, and soil, treating secondary type wastewater from a pig farm; Recsetar et al. (2021) evaluated *Sorghum bicolor* as the vegetation of lab-scale hydroponic beds filled with expanded clay for treating tertiary-type wastewater. However, *Sorghum* is the genus most referred to in the search carried out for bioenergy uses. The most referred application of *Sorghum* biomass was found as raw material for bioethanol production. In line with the observed relevance, at least 3 recent review works were dedicated to *Sorghum* spp. (all dedicated to sweet sorghum, *Sorghum bicolor*): Ahmad Dar et al. (2018) reviewed the use of sweet sorghum for bioethanol and biogas production; The review work of Appiah-Nkansah et al. (2019) also focuses on the production of bioethanol, and valorization of non-fermentable plant fractions for biogas production; Finally, the work of Stamenković et al. (2020) presents a review of additional routes for the conversion of sweet sorghum into biofuels besides bioethanol and biogas, such as biohydrogen, biodiesel production from sorghum grains, and other biofuels through thermochemical processes (liquefaction, pyrolysis, torrefaction, and gasification), and also direct combustion. In effect, the search carried out in the present work revealed that *Sorghum* spp. received research attention in all 9 bioenergy routes.

It should be highlighted that sorghum's main uses are in the food and feed markets, thus its use as bioenergy feedstock competes direct or indirectly with human consumption. However, growing sorghum in constructed wetlands does not pose this threat nor does it require arable land or potable water for irrigation. The same advantageous use of constructed wetlands applies to any bioenergy crops.

Brassica spp. are also rarely mentioned as constructed wetlands vegetation. However, this genus ranks second after *Sorghum* spp. in the search carried out on bioenergy applications. The most common species referred to as bioenergy uses is rapeseed (*Brassica napus*), which main bioenergy application is the production of biodiesel from the oil extracted from the plant seeds, which is one of the principal sources of first-generation biodiesel worldwide (Milazzo et al., 2013; Pari et al., 2020). Effectively, in the present work, the genus *Brassica* was retrieved as the most common plant for biodiesel production. However, plants of the *Brassica* genus were also popular in research for the evaluation of bioethanol production (using canola meal, *B. campestris* (Martins et al., 2020), and using rapeseed straw (Tan et al., 2020), for example), biogas production (for example using rapeseed straw (Wang et al., 2020), or canola straw (Safari et al., 2018)), and its use as raw-material for pyrolysis processing (using seeds of Indian mustard, *B. juncea* (Altamer et al., 2021), or rapeseed stalks (Gao et al., 2017), for example).

However, CW applications of plants from the genus *Brassica* are scarce. Chen et al. (2010) performed a screening of plants as constructed wetlands vegetation observing that *Brassica oleracea* (Cabbage) can be used but shows low purification potential. Abbasi et al. (2018) tested the purification potential of *B. juncea* in lab experiments. Later, Abbasi et al. (2019) carried out experiments in pilot-scale constructed wetlands vegetated with selected plants including the *B. juncea*, obtaining satisfactory results; Aiming to study the potential of 4 plants in constructed wetlands for treatment of wastewater generated during oil and gas extraction, Clay and Pichtel (2019) carried out hydroponic rhizofiltration experiments with *B. juncea* at lab scale; Fahim et al. (2020) conducted field experiments in a pilot-scale constructed wetland vegetated with a mix of 3 plants including *B. juncea*.

Miscanthus spp. ranks third in the bioenergy research popularity (Fig. 1), which main conversion processes studied according to this work are gasification, pyrolysis, aerobic fermentation, anaerobic digestion, and combustion, in this order (Table 3). Although *Miscanthus* spp. are more usual than *Sorghum* and *Brassica* spp. in CW applications, this genus is less common wetland vegetation. Most referred to is a hybrid specie known as Giant Miscanthus (*Miscanthus x giganteus*), claimed as suitable vegetation from some studies in pilot-scale CWs (Appiah-Nkansah et al., 2019; Marzec et al., 2019; Plestenjak et al., 2021; Sochacki et al., 2018; Toscano et al., 2015). The effective use of *M. floridulus* and *M. sacchariflorus* is also reported (Ge et al., 2011; Gorme et al., 2012).

Miscanthus was an object of various review works on its relevance as a biomass source for bioenergy applications. Some examples among other works are the review works of Babovic et al. (2012), Guzman and Lal (2014), Hu et al. (2017), and Wang et al. (2021), but focusing on bioethanol production. On the other hand, the review work of Daraban et al. (2015) refers to the potentiality of *miscanthus* biomass briquetting or palletization for heat generation by direct combustion. In line with the observed research intensity, several works concerning the suitability of miscanthus biomass for gasification (Couto et al., 2017; Samson et al., 2018; Sharma et al., 2018; Tursunov et al., 2020; Zamboni et al., 2016), pyrolysis (Conrad et al., 2019; Hu et al., 2021; Lakshman et al., 2021; Singh et al., 2021; Wang and Lee, 2018), anaerobic digestion (Kiesel and Lewandowski, 2017; Kupryś-Caruk and Podlaski, 2019; Mangold et al., 2019; Schmidt et al., 2018; Xue et al., 2020), and combustion (Bilandzija et al., 2017; Iqbal et al., 2017; Jensen et al., 2017; Lanzerstorfer, 2019) are available. So, plants of the genus *Miscanthus* seem to be a potential candidate to obtain a synergic use of CW as a driver for the water-energy nexus.

Saccharum spp. ranks fourth just below *Mischantus*, and above

Helianthus, in bioenergy research intensity (Fig. 1). On the other hand, there are few examples of using this genus of plants as CW vegetation. *S. bengalense* was studied as CW vegetation in bench-scale systems treating acid mine drainage waters (Sheoran, 2007). Sugarcane (*S. officinarum*) was first studied in lab-scale CW (Mateus et al., 2014), and further in pilot-scale CW (Herrera-López et al., 2021; Mateus et al., 2016, 2017). There are no dedicated works to evaluate the bioenergy potential of *S. bengalense*, but *S. officinarum* is one of the main raw sources for bioethanol production in the world (Hoang and Nghiem, 2021). Sugarcane farms including CW planted with sugarcane can be a way to improve the sustainability of the cane bioethanol industries through balanced land and water management. Moreover, there are examples of using CW for the treatment of sugarcane mills wastewaters (Batubara and Adrian, 2011; Tonderski et al., 2007), which represents a way to implement circular economy concepts.

Although bioethanol production from sugarcane is based on the processing of plant juice, and also on mixtures of juice and molasse residue from sugar production (Bermejo et al., 2020), sugarcane bagasse and straw show some potential to be used as raw materials but require pre-treatment steps (Ajala et al., 2021; Bermejo et al., 2020; Vieira et al., 2020). The trend in research increase on producing bioethanol from sugarcane processing waste such as bagasse and trash was verified by a recent review work (Figueroa-Rodríguez et al., 2019). Since bioethanol production from sugarcane generates large amounts of high organic and nutrients loaded wastewater (vinasse), this liquid residue can be valorized by anaerobic digestion to obtain biogas and biohydrogen, among other products (Silva et al., 2021). According to the results of the present work, biogas production using *Saccharum* spp. ranks second after bioethanol in the surveyed literature, followed by pyrolysis, gasification, and biohydrogen. In addition to the example of biogas production from vinasse, other sugarcane processing wastes such as bagasse (Agarwal et al., 2022), trash (Ketsub et al., 2021), and scum (Mendieta et al., 2020) were studied for biogas production. Pyrolysis processing is also focusing on sugarcane processing wastes such as bagasse (Barros et al., 2018; Veiga et al., 2021), straw (Barros et al., 2018; Charusiri and Vitidsant, 2017), and leaves (Charusiri and Vitidsant, 2018). The wastes from sugar or ethanol production are also the main studied raw materials in gasification experiments (Benedikt et al., 2018; Dirbeba et al., 2016; Fantini et al., 2014; Pedroso et al., 2017; Petersen et al., 2015). However, the entire aerial part of *S. spontaneum* was investigated as raw material for gasification, and further electricity generation by combined heat and power process (Aguilar et al., 2020). The surveyed literature shows an increasing trend in research on biohydrogen production from sugarcane byproducts. Most of the research focuses on bagasse valorization (Bu et al., 2021; Hu and Zhu, 2017; Huang et al., 2022; Rai et al., 2014; Reddy et al., 2017), vinasse (Fuess et al., 2019; Santos et al., 2014; Sydney et al., 2014), and molasses (Chaves et al., 2021; Li et al., 2020). However, the valorization of sugarcane leaves for biohydrogen production is also reported (Moodley and Kana, 2015).

Analyzing the data that form the basis of the results presented in section 3, the relevance of plant genera for each of the 9 bioenergy applications can be summarized as follows:

- Most referred plants for bioethanol production are *Sorghum* spp., *Saccharum* spp., and *Miscanthus* spp.;
- For biogas production are *Sorghum* spp., *Eichhornia* spp., and *Oryza* spp.;
- For biodiesel production are *Brassica* spp., *Helianthus* spp., and *Gossypium* spp.;
- For bio-hydrogen production are *Sorghum* spp., *Saccharum* spp., and *Agave* spp.;
- For combustion processes are *Miscanthus* spp., *Sorghum* spp., and *Salix* spp.;
- For gasification processes are *Miscanthus* spp., *Sorghum* spp., and *Panicum* spp.;
- For pyrolysis processes are *Miscanthus* spp., *Sorghum* spp., and *Gossypium*;
- For torrefaction processes are *Miscanthus* spp., *Gossypium* spp., and *Sorghum* spp.;
- And, for liquefaction processes are *Sorghum* spp., *Miscanthus* spp., and *Populus* spp.

Plants from the genera *Sorghum* and *Miscanthus* are extensively studied for a large range of bioenergy applications. However, *Miscanthus* species are less commonly applied as CW vegetation, and *Sorghum* species are scarcely studied in that role.

Although hydrogen can be obtained from the thermochemical processing of biomass, mainly by gasification, it was observed that the research on biohydrogen production by fermentation of wetlands plants is marginally low. Considering the growing interest in hydrogen as an energy vector, and a special player in the management of renewable energy sources through energy storage to balance irregular production/demand markets, the valorization of wetland biomass for hydrogen production may consist of a relevant opportunity.

5. Conclusions and directions for future research

Vegetation is a main component of CW, and to maintain high rates of wastewater treatment the plants need to be harvested. So, the harvested biomass can be used for land amendment, composting, biofuels, and other valuable uses or products. However, the evaluation of CW biomass valorization is seldom studied. Considering bioenergy application, CW vegetation presents the advantages of not using arable lands and not requiring fresh water for irrigation. Thus, surpassing the main critical issues in the production of dedicated energy crops.

This overview work identified that CW vegetation shows potential to be evaluated as raw material for bioenergy production, in all 9 bioenergy routes considered. Uncommon CW species such as *Sorghum* and *Miscanthus* showed to concentrate the research interest on bioenergy valorization. However, usual wetland plants such as *Phragmites*, *Typha*, *Eichhornia*, and *Lemna* are also well-referred to bioenergy applications. In any case, almost wetland vegetation received some research interest in its use as a bioenergy source.

Future work may be carried out to evaluate the cross-potential of plant species as CW vegetation, concerning its capacity to contribute to wastewater treatment, and its potential as a bioenergy source. The results presented in this first general overview support three main directions for future research:

I. Plants with proven energy potential should be fully evaluated as CW vegetation such as *Sorghum*, *Miscanthus*, *Brassica*, *Saccharum*, and *Gossypium*, among other genera;
II. Bioenergy valorization of CW vegetation should be systematically studied, with a focus on the use of the entire aerial part of plant biomass;
III. And, the potential recovery of CW vegetation for bioenergy applications can be viewed as part of the design and implementation of CW infrastructures.

It was found that the use of energy crops as CW vegetation is reduced even though some studies have demonstrated the adaptation of these plants to the CW flooded environments, without prejudice to the treatment efficiency. It is recommended that not only should the energy recovery of CW plant biomass be taken into account in the design phase, but that the use of energy crops as CW vegetation should also be further explored.

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CRediT authorship contribution statement

Henrique J.O. Pinho: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Dina M.R. Mateus:** Validation, Formal analysis, Investigation, Data curation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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