Journal of Environmental Management 369 (2024) 122258

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Review

Turning waste into resources: A comprehensive review on the valorisation of *Elodea nuttallii* biomass

Marta Zoppi [a,b,*], Elisa Falasco [a,b], Benoît Schoefs [c], Francesca Bona [a,b]

[a] DBIOS, University of Turin, Turin, Italy

[b] ALPSTREAM, Alpine Stream Research Center/Parco del Monviso, Ostana, Italy

[c] MetabolIsm, Molecular Engineering of Microalgal and Applications (MIMMA), Biologie des Organismes Stress Santé Environnement, IUML – FR 3473 CNRS, Le Mans University, Le Mans, France

ARTICLE INFO

Keywords:
Waterweed
Invasive alien species
Potential uses
Biogas
Circular economy
Plant biotechnology

ABSTRACT

This review focuses on the alternative uses of *Elodea nuttallii* (Planch.) H.St.John biomass. *Elodea nuttallii* is as an aquatic invasive alien species classified in the EU as a Species of Union Concern. Its dense monospecific stands affect both aquatic ecosystems and human activities, thereby requiring specific monitoring and management measures. The handling of *E. nuttallii* has a high economic cost, and the biomass removed from natural environments is considered a mere waste product. The need to implement circular economy, reducing waste and preserving natural capital, has led to the research for the reuse and valorisation of waterweed biomasses, such as *E. nuttallii*. This review critically assesses the feasibility and potential applications of *E. nuttallii* biomass in various sectors, including bioenergy production, extraction of metabolites, and fertilization. Out of more than 200 articles from 1965 to 2023, only 16 were found to deal with the use of harvested biomass, all within the last 12 years. This review highlights that the valorisation of *E. nuttallii* biomass is an underrepresented topic in scientific literature, and therefore in industrial sectors. Studies on biogas production are the most represented and have shown that *E. nuttallii* chemical composition is suitable for energy production, but is better suited as an additional feedstock to other biomasses already used for this purpose. New more cost-effective applications, such as animal feed and biosorbent, should be further addressed. By investigating alternative uses for *E. nuttallii* biomass, this review contributes to the development of sustainable practices that would turn a costly waste into a valuable resource.

1. Introduction

Invasive Alien Species (IAS) are allochthonous animals and plants that spread to a new environment, causing negative impacts that - in turn - affect ecosystem services, economy, and human health (IUCN, 2023). IAS are fully acknowledged as one of the five major causes of biodiversity loss worldwide (IPBES, 2023; IUCN, 2023). The European Commission recognises the threat of invasive species and the need for an internationally coordinated effort to prevent, minimize and mitigate IAS impact. Member States are required to undertake specific actions to limit new introductions, detect and eradicate, and manage invasive species (European Commission, 2017). In inland waters, a major threat is posed by aquatic weeds, which have caused multiple issues for aquatic ecosystems in recent years, in many cases requiring drastic management solutions. This is the case of *Elodea nuttallii* (Planch.) H.St.John (synonyms: *Anacharis nuttallii* Planch.; *Philotria minor* Small; *P. nuttallii* (Planch.) Rydb.; *E. minor* (Engelm.) Farw; *Udora canadensis* var. *minor* Engelm.; *P. occidentalis* House; *E. columbiana* St. John (Duenas, 2022), a perennial, submerged waterweed, native to temperate regions of North America (Casper and Krausch, 1981; Duenas, 2022). The spread of this plant outside its natural range is due to anthropogenic activities. *Elodea nuttallii* has been commercialised worldwide as an oxygenator and ornament for ponds and aquariums, and has been planted in aquaculture plants as a supplementary food source for fishes and crustaceans. Since it was first reported, dating back to 1914 in Great Britain or 1939 in Belgium depending on the authors (Josefsson, 2011; Millane et al., 2016; Simpson, 1984; Wolff, 1980), it has subsequently spread to 20 European countries. It has also invaded Southeast Asia (EPPO European and Mediterranean Plant Protection Organization, 2023; Fujiwara et al., 2020; Kadono, 2004; Koyama et al., 2014), and it is the first non-native

* Corresponding author. DBIOS, University of Turin, Turin, Italy.
E-mail address: marta.zoppi@unito.it (M. Zoppi).

https://doi.org/10.1016/j.jenvman.2024.122258
Received 2 May 2024; Received in revised form 25 June 2024; Accepted 19 August 2024
Available online 29 August 2024

freshwater weed in Alaska (Schwoerer and Morton, 2018; Wishnek and Dlugolecki, 2020). Since 2017, *E. nuttallii* has been included in the list of IAS of European Union Concern (Regulation EU 1143/2014 and Commission's Implementations), and is classified by the European and Mediterranean Plant Protection Organization (EPPO) as an A2 plant, "as having a high potential for spread; as posing an important threat to plant health and/or the environment and biodiversity; and eventually as having other detrimental social impacts in the EPPO region" (EPPO European and Mediterranean Plant Protection Organization, 2023; European Commission, 2014, 2017, 2019). Unlike *E. nuttallii*, other congeneric species are not officially classified as IAS of Union Concern in EU. The congeneric species *Elodea canadensis* has been significantly introduced outside its natural range, for example, in Europe. Although it has rapidly spread into new areas, after the more recent introduction of *E. nuttallii*, the latter often outcompetes *E. canadensis*, suggesting a decline of *E. canadensis* in favour of the invasion of *E. nuttallii* (Buldrini et al., 2023).

Elodea nuttallii prefers meso- or eutrophic habitats, shallow, slow-flowing, or standing waters. Artificial canals, ponds, and lakes are the most common habitats, but it also grows in streams and rivers, preferring muddy substrates, high concentrations of nitrogen and calcium, and low-velocity and low-turbulence waters (Kolada et al., 2022; Mazej Grudnik and Germ, 2013; Steen et al., 2019). Whenever the optimal conditions are encountered, plants can reach the water surface and form dense monospecific stands, thanks to rapid growth and dispersal, enhanced by vegetative propagation (Crane et al., 2022; Kunii, 1984; Preston and Croft, 2014). When it reaches a high biomass, *E. nuttallii* can have important repercussions on the ecosystem due to its role as an ecological engineer, *i.e.,* organisms that "directly or indirectly modulate the availability of resources to other species by causing physical state changes in biotic or abiotic materials" (Jones et al., 1994). In freshwater habitats, invasive ecosystem engineers impact environmental factors such as light, temperature, sediment deposition, nutrient availability, and oxygen level, altering habitat structure and water chemistry and posing a potential threat to other species (Emery-Butcher et al., 2020; Jones et al., 1994). *E. nuttallii* has been demonstrated to alter freshwater communities, in particular aquatic plants, macroalgae, phytoplankton, and invertebrates, by modifying oxygen saturation level, nutrient level, pH, light availability, and allelopathic interactions (Dembowska et al., 2021; Kelly et al., 2015; Szabó et al., 2010; Vanderstukken et al., 2014). As a result, biotic communities are qualitatively and quantitatively altered, showing different species composition and lower biomass, species richness and biodiversity, and ecosystem resilience to disturbances is reduced. In addition to the alterations of the ecosystem, the impact on environmental services and human activities is also significant (Di Nino et al., 2005; Millane et al., 2016; Steen et al., 2019). *Elodea nuttallii* dense stands interfere with both recreational (*e.g.*, bathing, angling, and other outdoor activities) and productive (*e.g.*, hydroelectric energy generation, boat traffic) activities.

Given the rapid spread of *E. nuttallii* outside its natural range over the last century, new restrictions and biosecurity measures are needed to reduce its future spread to uncolonized areas. Preventive measures include restrictions on the import and sale of potentially invasive species, an increase in monitoring and surveillance programs, and efforts to control the existing infestations. Still, many suitable areas (including some sites of the Natura 2000 protected network in the EU) are at high risk of invasion in the near future, given the high connectivity of waterbodies and the ease of *E. nuttallii* to reproduce through fragmentation (Steen et al., 2019). The prevention of the introduction and spread of *E. nuttallii* is a fundamental task, which is more cost and effort effective than subsequent intervention. However, in many European regions, but also outside the European Union, in Alaska, China, and Japan, it is too late for prevention, and intervention is mandatory. Remediation and management strategies are a real issue where the waterweed is already widespread. Control methods for aquatic weeds are biological control using herbivorous fish, chemical control (*e.g.*, herbicides), and mechanical control (*e.g.*, shading, water level drawdown, cutting) (Barrat-Segretain and Cellot, 2007; Cuthbert et al., 2019; Garland et al., 2022; He et al., 2019; Hoffmann et al., 2013; Zehnsdorf et al., 2015). Manual removal, mechanical cutting, and harvesting are the most effective and environmentally friendly control methods (CAISIE Control of Aquatic Invasive Species in Ireland, 2013), although these actions produce a huge amount of biomass that needs to be disposed of. For example, in 2004, approximately 26,000 metric tons of *Elodea* spp. fresh material was harvested in a 13 km^2 area of Lake Goitzsche, Germany (Bauer et al., 2018). In addition to the costs of labour and equipment, the costs associated with the disposal of the harvested biomass should also be considered. The risk assessment for *E. nuttallii* carried out by Millane et al. (2016) estimated the annual management costs for EU countries to be between 0.1 and 1 million € in 2016, rising to more than €13 M in the future. Macêdo et al. (2024) highlighted that annual global costs of damage and management of aquatic invasive plants have increased by three to four orders of magnitude since 1975. Most of the time, *E. nuttallii* harvested biomass is considered as organic waste and treated accordingly, but new utilizations as profitable alternatives to disposal are gaining attention. This is especially true from a circular economy perspective; the need to reuse, recycle, and recover the existing biomass is undeniable and this action is environmentally friendly and economically convenient in a broad viewpoint. In recent years, researchers and local authorities have had to optimise the removal of aquatic plant IAS from infested waters in terms of harvesting methods and alternative uses of the plant, considering biomass as a raw material for alternative uses rather than as a waste.

This review aims to summarize the current knowledge on possible alternative uses of harvested biomass of *E. nuttallii*, an IAS of Union Concern whose monitoring and management are mandatory in the EU, and to identify the main gaps that need to be filled by scientific research in the near future for an environmentally sustainable and economically viable management of *E. nuttallii*. Alternative uses tested for *E. nuttallii* may provide a starting point for managing other invasive macrophytes.

2. Methods

The objective of this review was to collect and critically assess scientific results concerning the possible reuse of *E. nuttallii* biomass in the context of a circular economy approach to waste management and valorisation. To this aim, bibliographic research was conducted by using Google Scholar, PubMed®, and Scopus® search engines. Firstly, papers containing the terms "*Elodea nuttallii*" AND "use*"; "*Elodea nuttallii*" AND "application*"; "*Elodea nuttallii*" AND "alternative*"; "*Elodea nuttallii*" AND "utilisation*" in their title/abstract/keywords were selected to obtain an overview of the topic. Papers i) not focusing on the species *E. nuttallii*; ii) quoting the terms without delving into new approaches, research, or results on the matter; iii) centring on ecological or physiological aspects of the plant or applications requiring *E. nuttallii* plantation were excluded. To comply with circular economy principles, only papers that concerned *E. nuttallii* harvested biomass as a raw material for innovative applications were considered, while we excluded research implying its cultivation. Based on the results obtained by this first selection, a second, more specific search was run, using the following words: "*Elodea nuttallii*" AND "energy*"; "*Elodea nuttallii*" AND "anaerobic digestion"; "*Elodea nuttallii*" AND "biogas" OR "methane"; "*Elodea nuttallii*" AND "hydrothermal" AND "treatment" OR "process" OR "carbonization"; "*Elodea nuttallii*" AND "biochar"; "*Elodea nuttallii*" AND "biofuel"; "*Elodea nuttallii*" AND "metabolite*"; "*Elodea nuttallii*" AND "pharmaceutical*"; "*Elodea nuttallii*" AND "fertilizer*"; "*Elodea nuttallii*" AND "agriculture"; "*Elodea nuttallii*" AND "feed" OR "food"; "*Elodea nuttallii*" AND "sorption" OR "biosorption" OR "adsorption" OR "remediation". The selected papers were screened as illustrated above. Moreover, grey literature was excluded from the review (*i.e.*, abstracts in books of conferences, posters, technical reports, and theses). To delve into molecular and pharmaceutical aspects, the PubChem® search

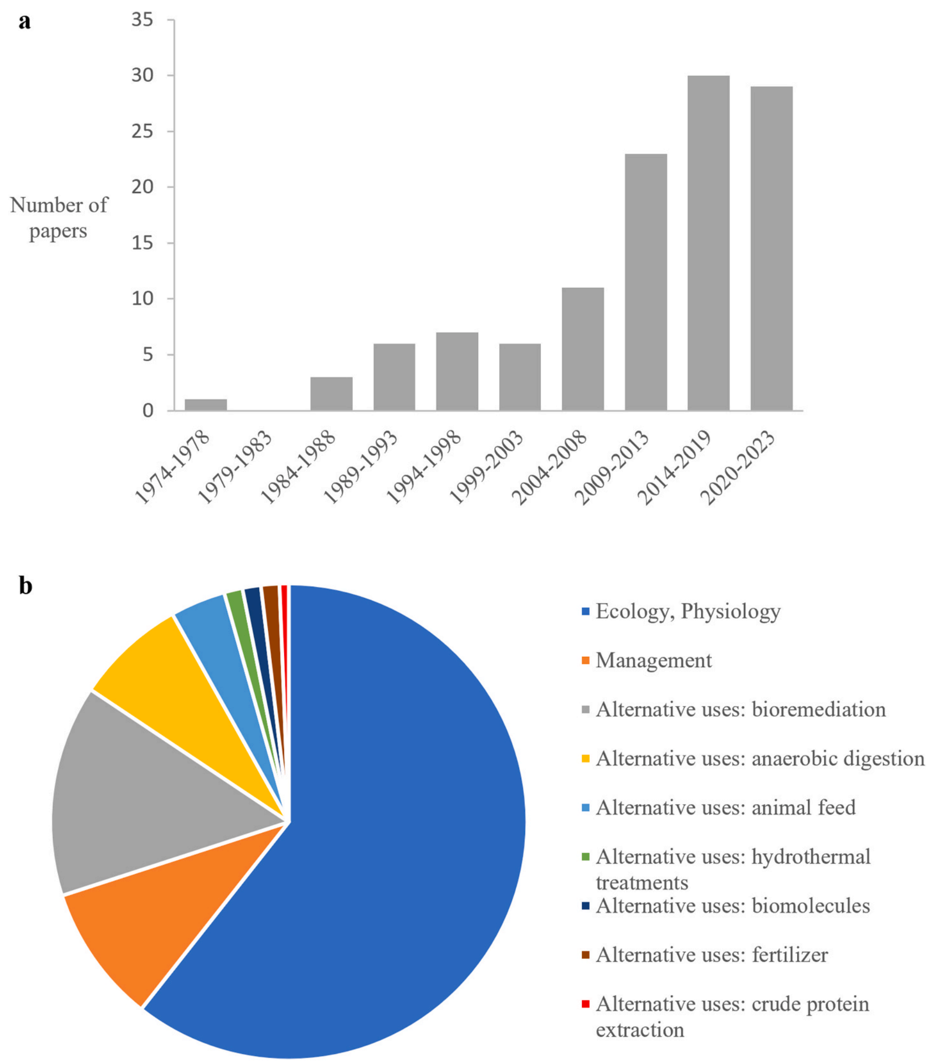

Fig. 1. Papers concerning *E. nuttallii* that resulted from the bibliographic survey. a) Time trend. b) Main topics of the papers.

engine was used.

3. Results

The first general query resulted in more than 200 scientific papers dating from 1965 to 2023, of which 75% were published in the last decade (Fig. 1 - a). The main topics of these publications were ecology, physiology, management, and alternative uses based on alive or dead biomass of *E. nuttallii* (Fig. 1 – b. Supplementary Material for more details). Among them, the vast majority were excluded, and only 14 papers were selected as truly focusing on the application of *E. nuttallii* harvested biomass. The second survey detected around 20 papers that were not included in the first research, but only two concerned our topic.

The bibliographic survey highlights that the scientific interest in the recovery and reuse of *E. nuttallii* biomass is quite recent: the first paper about potential uses of *E. nuttallii* dates back to 2011, and 31% of the 16 selected articles about this topic were published in 2018 by authors working in Germany. Despite the need for favourable management strategies for invasive waterweeds and the current attention to sustainable and circular economy-based approaches, alternative uses of *E. nuttallii* have rarely been investigated, and this review emphasizes the requirement for more research on this topic to implement *E. nuttallii* handling and to use it as a model for other invasive alien macrophytes. At present, the applications of *E. nuttallii* that have been tested in the scientific literature are: (i) biogas production through anaerobic digestion; (ii) hydrothermal treatments for solid biofuel production; iii) the extraction of metabolites for pharmaceutical use; and (iv) the production of fertilizer.

3.1. Biogas production through anaerobic digestion

From this research, energy production from plant biomass resulted as the most investigated topic for the valorisation of *E. nuttallii* harvested biomass as an alternative to plant disposal. Anaerobic digestion (AD) is a technology that provides energy in the form of biogas (*i.e.*, a mixture of methane, carbon dioxide, and other gases produced by the fermentation of organic matter) and digested liquid and solid effluents through anaerobic biochemical conversion of organic compounds. A digester could operate with many organic feedstocks, *e.g.*, livestock slurry and manure, food waste, crop silage, wastewater sludge, or with a co-digestion of more than one substrate (Zhang et al., 2016). AD is widely employed to produce renewable alternative energy and to implement cost-effective and environmentally friendly management of wastes: in 2020, there were 18,843 biogas plants in Europe, and this number has been significantly increasing by year (EBA European Biomass Association, 2022). Methane is the primary component of the biogas produced by AD (around 60%) and is used as a fuel source of energy (Holmes and Smith, 2016).

In the following paragraphs, the chemical composition and storage of *E. nuttallii* biomass are discussed as important aspects to consider for

Table 1
Composition of some lignocellulosic biomasses tested for anaerobic digestion.

Biomass	Cellulose %	Hemicellulose %	Lignin %	Units	Lignin/Cellulose	References
E. nuttallii	16.5	24.7	n.d.	% DW	/	Xiao et al., 2009
E. nuttallii	35.9	n.d.	3.2	% TS	0.1	Koyama et al., 2014
E. nuttallii	21.8–55.6 % TS	7–9.5 % DW	n.d.		/	Atapaththu et al., 2015
E. nuttallii	17.5	4.7	2.2	% TS	0.1	Gallegos et al., 2018
E. nuttallii	21.5–40	3.1–9.2	6.2–15.3	% VS	0.3–0.4	Fujiwara et al., 2020
Alterranthera philoxerides	25.4	27.1	n.d.	% DW	/	Xiao et al., 2009
Azolla filiculoides	21.8	13.5	10.3	% VS	0.4	Miranda et al.
Ceratophyllum demersum	22.3	6.9	15.8	% TS	0.7	Koyama et al., 2014
Egeria densa	36.2	1.9	4.4	% TS	0.1	Koyama et al., 2014
Egeria densa	29.2–35.3	7.7–16.9	3.1–9.2	% VS	1.1–0.3	Fujiwara et al., 2020
Eichhornia crassipes	24.5	34.1	8.6	% VS	0.4	Ruan et al., 2016
Hydrilla verticillata	356.1–394.5	9.4–20.3	11.1–17.7	% VS	≈0	Fujiwara et al., 2022
Lemna sp.	10–24.5	3.5	3.1	% VS	0.1–0.3	Xu and Deshusses, 2015
Pistia statiotes	27.6	29.7	3.5	% VS	0.1	Sivasankari and Ravindran, 2016
Potamogeton maackianus	23.1–30.8	12.3–18.5	15.4–23.1	% VS	0.6–0.8	Fujiwara et al., 2020
Salvinia molesta	32	26	13.7	% VS	4.3	Sciessere et al., 2011
Spirodela polyrhiza	20.2	17.9	13.3	% VS	0.7	Fujiwara et al., 2022
Trapa japonica	22.9	10.1	9.2	% VS	0.4	Fujiwara et al., 2022
Typha latifolia	38.5	37	12.8	% VS	0.3	Sopajarn and Sangwichien, 2015
Vallisneria natans	12.3	28.2	n.d.	% DW	/	Xiao et al., 2009

DW: dry weight, TS: total solids, VS: volatile solids.

efficient AD, followed by a subsection regarding biogas production.

3.1.1. Chemical composition of the biomass

Submerged macrophytes have a softer body structure than terrestrial plants and emerging aquatic plants, owing to a low lignin content. The low ratio between lignin and cellulose and hemicellulose, which is typical of aquatic plants, enhances the methane production in AD plants (Fujiwara et al., 2022; Kaur et al., 2018; Koyama et al., 2014) (Table 1). Table 1 shows cellulose, hemicellulose and lignin content in 15 aquatic plants, and it emphasizes the suitability of *E. nuttallii* for AD, having a lignin:cellulose ratio that ranges from 0.1 to 0.4, whereas in other species it reaches higher values, up to 4.3 in *Salvinia molesta*. On the other hand, the high water content of aquatic plants (up to 95% of dry mass in *E. nuttallii*) is a critical factor for digesters. This aspect complicates both processing, as the digestate is in a more diluted form and biogas production is lower from fresh biomass, and storage, given that the waterweed begins to decompose rapidly in the open air (Bauer et al., 2018; Möller et al., 2018). Knowledge of the chemical composition of the substrate is essential to obtain good AD performances, high methane production, and a valuable digestate. Researchers highlight a common trend between biomass composition in terms of lignin, total carbon and total nitrogen content, and methane yield (Fujiwara et al., 2020; Koyama et al., 2014). The C:N ratio is another key factor in digestion processes. In *E. nuttallii* it has been reported between 10.8 and 31.8, almost fitting the optimal (*i.e.* 15 and 30; Fujiwara et al., 2020; Möller et al., 2018; Zehnsdorf et al., 2017, 2018).

Fujiwara et al. (2020) pointed out that seasonality could affect the biochemical composition of weeds and, therefore, their methane potential. For example, *E. nuttallii* showed a marked seasonality in the lignin content, with the lowest values during summer and the highest values in autumn with leaf loss. This is a positive feature of this species, as the time of year, when the percentage of lignin is the lowest, is also the time when the available biomass is at its maximum.

Special attention must be paid to the potential presence of xenobiotics in AD feedstocks, which can be absorbed from water, compromising AD performances and biogas development. Heavy metals and other pollutants, like antibiotics and chlorophenols, which are used as pesticides, herbicides, antiseptics, and fungicides, have notably toxic effects on methanogenic bacteria, causing a reduction in the yield of biogas and the production of intermediate organic compounds (Czatzkowska et al., 2020). A significant presence of these pollutants in the digestate could be an obstacle to its subsequent use, for example, as a fertilizer. Zehnsdorf et al. (2017) reported low concentrations of chromium, cadmium, nickel, lead, and zinc in *E. nuttallii* dry matter, with no negative consequences for AD and digestate use.

Table 2
Comparison of methane yields generated by AD of different feedstocks.

Feedstock	Composition	Methane yield mL CH_4/g VS	References
E. nuttallii	Fresh *E. nuttallii*	261–301	Muñoz Escobar et al., 2011
E. nuttallii	Fresh and chopped *E. nuttallii*	204–233	Möller et al., 2018
E. nuttallii	Frosted and shredded *E. nuttallii*	360	Koyama et al., 2014
E. nuttallii	Dried and milled *E. nuttallii*	189.2–284.1	Fujiwara et al., 2020
Elodea silage	*E. nuttallii* silage	219	Zehnsdorf et al., 2018
Mixed silage	*E. nuttallii* and chopped and ground straw silages	166–228	Zehnsdorf et al., 2018
Elodea silage	*Elodea* spp. silage	215	Gallegos-Ibanez et al., 2023
Mixed silage	*Elodea* spp. and chopped and ground wheat straw silages	167–226	Gallegos-Ibanez et al., 2023
Silage mixtures of *Elodea* and wheat straw	*Elodea* spp. silage (20% *E. nuttallii*, 80% *E. canadensis*), wheat straw	166–228	Gallegos et al., 2018
Elodea straw silage	*E. nuttallii*, chopped wheat straw	259	Bauer et al., 2018
E. nuttallii process water	Water- soluble organic components from *E. nuttallii* undergone hydrothermal carbonization	283–287	Poerschmann et al., 2015
Swine manure	Swine manure	240	Vítěz et al., 2015
Dairy manure	Dairy manure	192	Ekinci et al., 2023
Rye grass silage	Rye grass silage	230–406	Vítěz et al., 2015
Corn silage	Corn silage	296	Labatut et al., 2011

VS: volatile solids.

3.1.2. Storage

Concerning the storage of wet and highly decomposable biomasses, some authors proposed ensiling for aquatic plants. Ensiling is based on solid-state lactic acid fermentation under anaerobic conditions

Table 3
List of the 10 most abundant and 10 unique molecules (signature molecules) found in *E. nuttallii* by Tang et al. (2023).

Molecule	Most abundant	Signature molecule	Family of compound		Other source	Biological activity
			Primary	**Secondary**	/	
1,2-Dipalmitoyl-*sn*-glycero-3-phosphate		✓	Lipid	/	/	?
2-deacetoxytaxinine B (2)	✓		Diterpene	Taxan	*Taxus cuspidata* (Liang et al., 1998), *T. wallichiana* (Kim and Yun-Choi, 2010; Shrestha et al., 1997)	+ Antiplatelet agent (Liang et al., 1998)
2-hydroxyhexadecanoic acid	✓		Lipid	FAME	Land plants (Shepherd et al., 2007)	–
2-methyl-5-(8-pentadecenyl)-1,3-benzenediol	✓		Lipid	Alkyl resorcinols and derivatives	Nuts (Mubofu and Mgaya, 2018), roots of *Ardisia cornudentata* (Chang et al., 2011)	+ Antitubercular (Chang et al., 2011), tyrosinase inhibitor (Kubo et al., 1994)
4′-O-(GlcA(1–2)GlcA) apigenin		✓	Polyphenol	Flavonoid glucuronide	Common in land plants	–
9,12,15-octadecatrien-1-ol	✓		Lipid	Fatty alcohols	Land plants	+ (Kim et al., 2024)
10,13-epoxy-10,12-octadecadienoic acid [5-pentyl-2-furanoctanoic acid]	✓		Lipid	Fatty acid	/	+ If concentration is equal to 100 μM or higher (Lengler et al., 2012)
(10*E*,15*Z*)-9,12,13-trihydroxyoctadeca-10,15-dienoic acid	✓		Lipid	Hydroxy fatty acid	Rhizomes of *Cyperus rotundus* (Shin et al., 2015), roots of *Malva symvestris* (DellaGreca et al., 2009), *Arabidopsis thaliana* (Mönchgesang et al., 2016; Strehmel et al., 2014), *Corchorus olitorius* (Yoshikawa et al., 1998)	+ Macrophage inactivation (Shin et al., 2015)
12*S*-hydroxy-5*Z*,8*E*,10*E*-heptadecatrienoic acid [12*S*-HHTrE]		✓	Lipid	Leukotriene	/	+ Not reported for the native compound, but metabolites can be active (Liu et al., 2014)
13(*S*)-Hydroperoxylinoleic acid		✓	Lipid	Degradation compound	/	–
C16 sphinganine	✓		Lipid	Sphingolipid	Land plants (Chao et al., 2011), fungus (Gacem et al., 2020)	+ (Gacem et al., 2020)
Eremopetasitenin C2		✓	Lipid	Sesquiterpene	*Petasites japonicus* (Tori et al., 1998)	?
Ethyl 7-epi-12-hydroxyjasmonate glucoside		✓	*O*-acyl carbohydrate	/	*Malus domestica* (ChEBI Chemical Entities of Biological Interest, 2024)	–
Gynocardin		✓		Cyanogenic glycoside	*Ryparosa kurrangii*	–
Harderoporphyrin	✓		Close tetrapoyrrole	Porphyrin	Usually, this compound is not accumulated	–
Lansioside C		✓	*O*-glucoside	/	Fruits (HMDB The Human Metabolome Database, 2024)	+ (Nishizawa et al., 1983)
***p*-chlorophenylalanine**	✓		Amino acid	/	/	+ (Dringenberg et al., 1995)
Phosphatidylinositol lyso 18:0		✓	Lipid	Glycerophospholipid	/	+ (Sabogal-Guáqueta et al., 2018)
Spirotaccagenin			Lipid	Triterpenoids	/	?
Sucrose	✓		Sugar	Disaccharide	/	?

(Weinberg and Ashbell, 2003). The objective of ensiling is to preserve plant material, maintaining as much as possible its original nutritional value. The quality of the obtained silage is evaluated by texture, dry matter loss, pH, temperature, fermentation, and lactic acid production. Silage quality improved particularly when *Elodea* spp. was ensiled with wheat straw, whereas enzymatic, chemical, and bacterial additives did not seem to have any benefit on silage (Gallegos-Ibanez et al., 2023; Zehnsdorf et al., 2018).

3.1.3. Biogas production

Elodea nuttallii proved to have suitable characteristics for biogas production (Gallegos et al., 2018; Koyama et al., 2014; Möller et al., 2018), and it showed the highest methane yield among five submerged macrophytes (namely *Ceratophyllum demersum*, *Egeria densa*, *Potamogeton maackianus*, and *Potamogeton malaianus*) harvested from Lake Biwa, the largest lake in Japan (Koyama et al., 2014). Literature shows that the methane yield obtained with *E. nuttalli* as a substrate in AD processes is comparable with that of more traditional substrates, such as crop silage and manure (Table 2). Also, testing *E. nuttallii* silage in AD, researchers obtained a good methane yield (166–228 mL CH4/g VS) (Gallegos et al., 2018; Zehnsdorf et al., 2018).

Generally, researchers agree that biogas production with *E. nuttallii* is technically feasible, though not always cost-effective. Indeed, water-weed intrinsic characteristics (*e.g.*, C:N ratio, lignin and water content, rapid deterioration), and features linked to environmental conditions (*e.g.*, seasonal changes in the composition of the biomass and biomass availability) suggest that the most feasible use of *E. nuttallii* is as a co-substrate with other feedstock, such as wheat straw or maize silage (Bauer et al., 2018; Gallegos et al., 2018; Muñoz Escobar et al., 2011; Zehnsdorf et al., 2011, 2018). Further trials are needed, and new technologies, such as the two-stage serial wet- and solid-state AD (SS-AD) system proposed by Iweh et al. (2020), need to be further improved for a cost-effective AD treatment of *E. nuttallii* biomass.

3.2. Hydrothermal treatments

Hydrothermal treatments (HTs), including pyrolysis and hydrothermal processing, are interesting technologies to valorise humid biomass. These technologies use high temperature (up to 375 °C) and pressure (up to 22 MPa) to transform the biomass into solid, liquid, and gaseous products. The quality of the products and their potential applications depend on both the structure of the raw material and process conditions, such as temperature, pressure, time, and the use of a catalyst (Czerwińska et al., 2022; Demirbaş and Arin, 2002; Tekin et al., 2014).

The pyrolysis subproduct, *i.e.,* the biochar, can be used as a high-energy fuel, for soil carbon sequestration and improvement, or for absorption of liquid pollutants. The liquid phase is useful as a microalgae culture medium, fertilizer, or for biogas production. Finally, the employment of biogas as a renewable energy and fuel source (Czerwińska et al., 2022; Muñoz Escobar et al., 2011) has been discussed in the above section *Biogas production through anaerobic digestion*.

Few studies have focused on the utilisation of *E. nuttallii* biomass in HTs. Muñoz Escobar et al. (2011) and Poerschmann et al. (2015) tested the production of biochar from *E. nuttallii* biomass by hydrothermal carbonization. The solid products obtained from *E. nuttallii* seem potentially suitable for carbon sequestration, soil amelioration, and energy recovery in combustion plants. In general, the results showed a favourable solid conversion (59.5–65% on a weight basis; Muñoz Escobar et al., 2011), similar to that of other raw materials that underwent hydrothermal carbonization. The high retention of phosphorus and calcium in biochar makes them a good material for soil fertilization; on the other hand, the enrichment of potential phytotoxic elements (such as heavy metals like copper, zinc, aluminium) in the solid pellets is an unfavourable factor for agricultural use. As for energy production, *E. nuttallii* biochar demonstrated a low calorific value due to its high ash content and low organic carbon content. The quality of the biochar depends on the carbonization condition (*e.g.*, biochar obtained at 240 °C has a higher calorific value than that generated at 200 °C; Poerschmann et al., 2015). The low quality of solid fuels obtained from *E. nuttallii* was also highlighted by Pels et al. (2014).

The possible uses of the liquid products of hydrothermal carbonization have also been tested, for example, process water has been successfully used to produce biogas through AD. The liquid phase obtained from hydrothermal carbonization of *E. nuttallii* had a positive outcome in terms of methane yield (Table 2) (Poerschmann et al., 2015), which was even higher than the results obtained from other more traditional feedstock process water (*i.e.,* wheat straw), suggesting a viable application for the liquid products of HTs.

In conclusion, the main advantage of HTs is in the circular economy because they create new material, prolong the life of the raw material, and all the resulting products may be used for various applications, such as energy production, bioremediation, and fertilization. Specifically, products obtained from *E. nuttallii* were not suitable as a biofuel, but rather for soil fertilization and amelioration, and biogas production. HTs could be potentially sustainable methods (Zhang et al., 2023) for the valorisation of *E. nuttallii* biomass, but additional investigations and advancements are needed to better manage waterweed harvested biomass and to take the best advantage of all the products of the treatment.

3.3. Metabolites for pharmaceutical applications

Numerous aquatic plant species have been traditionally used in folk/traditional medicines and are known for having pharmaceutical applications, such as anti-inflammatory, antioxidant, antimicrobial, antipyretic, analgesic properties, and other specific activities (Baek et al., 2021; Osama et al., 2023; Rezq et al., 2021; Unadkat and Parikh, 2021). To date, studies on *E. nuttallii* metabolites and their potential pharmaceutical or nutraceutical applications are very scarce. In the second half of the 20th century, it was only known that *E. nuttallii* does not contain toxic substances (Hegnauer, 1963) and therefore can be used for food and/or feed. An initial search for the presence of active molecules in *E. nuttallii* was performed by Muñoz Escobar et al. (2011) who identified β-sitosterol, a common plant phytosterol. From the chemical point of view, β-phytosterol is similar to cholesterol. It exhibits many biological actions such as antioxidant, anticancer, anti-diabetic, antimicrobial and immunomodulatory activities (Bin Sayeed et al., 2016; Khan et al., 2022) and is also used for treating prostate hyperplasia (Wilt et al., 1999). The first analysis of the metabolome of *E. nuttallii* was published in 2023 by Tang and collaborators through a comparison with the metabolites contained in *Cladophora* sp., a freshwater green macroalga sharing the same environment. Because the aim of that study was to compare both metabolomes, the data were treated in order to enlighten the differences between them. At least 414 metabolites were identified, among which 10 compounds were the most abundant and 10 others constituted the metabolic signature of *E. nuttallii* regarding *Cladophora* (Table 3). Interestingly, none of the molecules appears in both lists. The list of compounds is additionally biased by the extraction protocol that was designed for extracting non-polar molecules. Among the 20 molecules identified in *E. nuttallii*, 10 have been already identified as presenting a biological activity while 6 do not have such an activity. The others have not yet been tested.

Table 4
Phosphorous content in digestate derived from AD of various substrates. P content has been evaluated with respect to digestate dry weight (kg DW), fresh weight (kg FW), or total solids (kg TS).

Feedstock	P concentration g/kg	References
E. nuttallii	2.4–3.1 g/kg TS	Stabenau et al., 2018
Energy crops	0.9–1.1 g/kg FW	Möller et al., 2010
Aloes peel	11.8 g/kg FW	Wang et al., 2019
Corn	11.6 g/kg FW	Wang et al., 2019
Agricultural lignocellulosic waste	0.9 g/kg DW	Tuszynska et al., 2021
Fruit and vegetable waste	2.4 g/kg DW	Tuszynska et al., 2021
Distillery residue	0.6 g/kg DW	Tuszynska et al., 2021
Household waste	3.1 g/kg TS	Grigatti et al., 2015
Maize	6.7 g/kg TS	Grigatti et al., 2015

In general, the concentration of these metabolites is lower in *E. nuttallii* than in other plants. For example, *E. nuttallii* has a maximal content of β-sitosterol of around 462 ppm (1 ppm = 1 mg β-sitosterol/1 kg *E. nuttallii* dry material), compared to 6200 ppm in the woodland hawthorn *Crataegus laevigata* (Muñoz Escobar et al., 2011). Nevertheless, the harvested biomass of the waterweed remains a waste, without the additional cost of cultivation and lacking in profiting alternatives. For this reason, the extraction of molecules from *E. nuttallii* could still be an economically viable alternative to be further examined not only from the pure economic point of view but also from the point of view of IAS management. Moreover, after extraction, the biomass can be used for other applications (*e.g.*, AD, HTs), increasing the circularity of the process. As an example, Tedesco and Stokes (2017) performed AD of algae biomass after the extraction of bioproduction, and they found that methane yield did not differ significantly from that obtained by un-extracted algae.

3.4. Use as fertilizer

Thanks to its rich macro- and microelement composition (nitrogen, phosphorous, potassium, magnesium, calcium, iron, sulphur, and the trace elements cobalt, copper, and zinc), *E. nuttallii* biomass is a complete organic fertilizer (Muñoz Escobar et al., 2011). However, the waterweed demonstrates a low decomposition rate, taking up to years in the soil to decompose due to the relatively high cellulose content. Its slow breakdown makes *E. nuttallii* raw material inadequate for field fertilization. On the other hand, waste material derived from other *E. nuttallii* treatments, *e.g.*, AD and HT, are a suitable alternative for fertilization purposes as such or as compost (Pels et al., 2014; Poerschmann et al., 2015; Stabenau et al., 2018). During processes like AD or HTs, various elements, such as nitrogen, phosphorus, and potassium, accumulate in the water instead of being converted into gas or solid products. An enriched liquid phase is produced, with a high nutrient content and no decomposition-related issues. *Elodea nuttallii* digestate was found to have a medium-high phosphorus concentration compared to other plant-based digestate (Table 4).

The possibility of using the digestate in agriculture always depends on its content in putative toxic elements such as heavy metals. These contaminants are regulated in agriculture by legal limits, and the

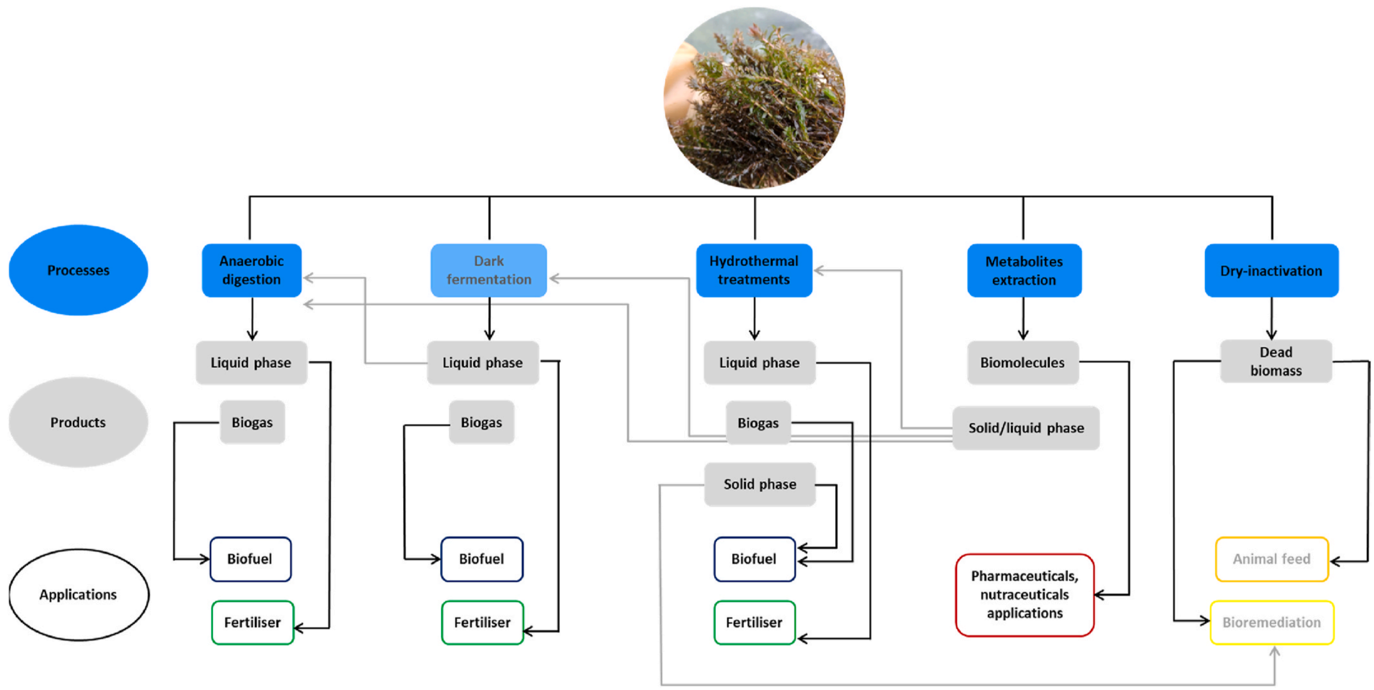

Fig. 2. Schematic summary of the potential uses of harvested biomass of *E. nuttallii* and connections among them. Applications which have not been tested yet are reported with higher transparency.

bioaccumulation capacity is plant-specific and depends on the environmental concentration of the xenobiotic. For this reason, the possibility of using *E. nuttallii* digestate as fertilizer must be always accompanied by a comparison of toxic elements concentrations in the biomass and in the environment (*i.e.*, in water and sediment).

4. Future perspectives

AD, HTs, metabolite extraction, and fertilization are applications of *E. nuttallii* biomass that have been tested in the scientific literature and discussed in the previous sections. Three innovative applications to be explored in the future are:

i) The use of *E. nuttallii* inactivated biomass as animal feed. Fresh *E. nuttallii* showed positive effects on growth, body size, and muscle quality of crustaceans and fishes (Dorenbosch and Bakker, 2011; Wu et al., 2023; Zheng et al., 2022). Indeed, other aquatic macrophytes (including IAS) have already been tested as dried feed ingredients for fish, poultry, and livestock, showing good nutritional potential and reducing costs and environmental impacts compared to traditional ingredients (Kumar et al., 2022; Naseem et al., 2021).

ii) The use of *E. nuttallii* inactivated biomass as biosorbent. Non-living macrophytes, including biochars, proved to be effective biosorbents for heavy metals, dyes, nitrogen, and phosphorus from water (Bianchi et al., 2021; Song et al., 2019; Wang, 2010; Xu et al., 2020). The sorption capacity of a dead-plant material depends on its physicochemical composition, particularly on surface functional groups. Colzi et al. (2018) compared the effectiveness of dead and living *Myriophyllum aquaticum* for heavy metals removal and obtained a higher removal percentage by using the non-living biomass, especially for Cd and Zn. Living *E. nuttallii* has been proven to adsorb metals (*i.e.*, mercury, cadmium, uranium), nutrients (*i.e.*, phosphorus, ammonium, nitrate), and fluoride from water and sediment (Cosio, 2020; Xiong, 2019; Zhou et al., 2012).

iii) The use of *E. nuttallii* biomass as a substrate for biohydrogen production. As far as the production of biogas from *E. nuttallii* biomass is concerned, current research only considers methane, a strong greenhouse gas, whose combustion releases carbon dioxide. In contrast, hydrogen is emerging as a promising cleaner-burning biofuel that produces only water vapour that can be collected for other usages (Ubando et al., 2022; Xu et al., 2022). *Elodea nuttallii* is a good candidate as a substrate for dark fermentation processes producing biohydrogen.

To our knowledge, Life Cycle Assessments (LCAs) and economic evaluations of the applications of *E. nuttallii* are currently missing in the scientific literature. Costs are one of the main issues related to IAS management and biomass valorisation. Nevertheless, the application of the biorefinery concept is more eco-friendly and it converts biomass to energy and other beneficial byproducts, with proper value. Feasibility studies are essential to establish management strategies and to develop full-scale applications, and they are an important aspect to be developed besides the testing of new applications.

5. Conclusions

The development of greener biotechnological processes and circular bioeconomy has motivated new research on alternative uses of *E. nuttallii* to disposal or incineration. This review article has provided a critical view of literature dealing with the use of *E. nuttallii* harvested biomass for energetic or pharmaceutical purposes. This biomass has demonstrated to be a suitable substratum for AD and HTs. Moreover, *E. nuttallii* byproducts have good characteristics to be used as fertilizers and the biomass contains at least 10 biologically active molecules. While most studies showed promising results, several knowledge gaps, areas of persistent uncertainty, and methodological issues do emerge from our analysis and need to be filled. Among others, high water content and decomposability are obstacles for treatments, and the efficacy of HTs liquid and solid phases as energy fuel, fertiliser, soil improver or liquid pollutant absorber should be further tested. Overall, more in-depth analyses, economic evaluations, and LCAs are needed to establish the real potentials of *E. nuttallii* and to optimise its valorisation. The challenge is to find solutions that are adapted to the characteristics of this biomass, considering that its production is season- and weather-dependent and unstable over time. Therefore, a scale-up of biorefinery process of *E. nuttallii* biomass will also require the supply of source of biomass others than *E. nuttallii*, which will be an additional feedstock, rather than the only one. Indeed, the same is true for well-established agricultural feedstocks, whose supply is discontinuous during the year. In addition, we suggest that a sustainable approach should consider different treatments and the possible connections within them, as summarized in Fig. 2, where we also included potential alternatives not yet explored.

Funding

This publication is part of the project NODES which has received funding from the MUR – M4C2 1.5 of PNRR funded by the European Union - NextGenerationEU (Grant agreement no. ECS00000036).

The funding source was not involved in the study design; in the collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the article for publication.

CRediT authorship contribution statement

Marta Zoppi: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Elisa Falasco:** Writing – review & editing, Visualization, Methodology. **Benoît Schoefs:** Writing – review & editing, Writing – original draft, Visualization. **Francesca Bona:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Marta Zoppi reports financial support was provided by European Union - NextGenerationEU (Grant agreement no. ECS00000036). If there are other authors, they 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

No data was used for the research described in the article.

Acknowledgments

This publication is part of the project NODES which has received funding from the MUR – M4C2 1.5 of PNRR funded by the European Union - NextGenerationEU (Grant agreement no. ECS00000036).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.122258.

References

Atapaththu, K.S., Miyagi, A., Atsuzawa, K., Kaneko, Y., Kawai-Yamada, M., Asaeda, T., 2015. Effects of water turbulence on variations in cell ultrastructure and metabolism of amino acids in the submersed macrophyte, *Elodea nuttallii* (Planch.) H. St. John. Plant Biol. 17 (5), 997–1004. https://doi.org/10.1111/plb.12346.

Baek, G., Saeed, M., Choi, H.K., 2021. Duckweeds: their utilization, metabolites and cultivation. Applied Biological Chemistry 64, 73. https://doi.org/10.1186/s13765-021-00644-z.

Barrat-Segretain, M.H., Cellot, B., 2007. Response of invasive macrophyte species to drawdown: the case of *Elodea* sp. Aquat. Bot. 87 (4), 255–261. https://doi.org/10.1016/j.aquabot.2007.06.009.

Bauer, A., Möller, L., Wedwitschka, H., Stinner, W., Zehnsdorf, A., 2018. Anaerobic digestion of mixed silage of waterweed biomass and wheat straw in a long-term semi-continuous biogas production process. Energy, Sustainability and Society 8 (1), 1–7. https://doi.org/10.1186/s13705-017-0145-9.

Bianchi, E., Coppi, A., Nucci, S., Antal, A., Berardi, C., Coppini, E., Fibbi, D., Del Bubba, M., Gonnelli, C., Colzi, I., 2021. Closing the loop in a constructed wetland for the improvement of metal removal: the use of *Phragmites australis* biomass harvested from the system as biosorbent. Environ. Sci. Pollut. Control Ser. 28, 11444–11453. https://doi.org/10.1007/s11356-020-11291-0.

Bin Sayeed, M.S., Karim, S.M.R., Sharmin, T., Morshed, M.M., 2016. Critical analysis on characterization, systemic effect, and therapeutic potential of beta-sitosterol: a plant-derived orphan phytosterol. Medicines (Basel) 15 (4), 29. https://doi.org/10.3390/medicines3040029.

Buldrini, F., Pezzi, G., Barbero, M., Alessandrini, A., Amedei, L., Andreatta, S., et al., 2023. The invasion history of *Elodea canadensis* and *E. nuttallii* (Hydrocharitaceae) in Italy from herbarium accessions, field records and historical literature. Biol. Invasions 25, 827–846. https://doi.org/10.1007/s10530-022-02949-6.

[CAISIE] Control of Aquatic Invasive Species in Ireland, 2013. Control of Aquatic Invasive Species and Restoration of Natural Communities in Ireland Project LIFE/NAT/IRL/000341. Best practice for control of Nuttall's pondweed. http://caisie.ie/wp-content/uploads/2013/06/D-10.7-Effective-control-measures-for-Nuttalls-pondweed.pdf (Accessed 15 April 2024).

Casper, S.J., Krausch, H.D., 1981. Familie hydrocharitaceae. Süßwasserflora von Mitteleuropa 2/2, 186–207.

Chang, C.P., Chang, H.S., Peng, C.F., Lee, S.J., Chen, I.S., 2011. Antitubercular resorcinol analogs and benzenoid C-glucoside from the roots of *Ardisia cornudentata*. Planta Med. 77 (1), 60–65. https://doi.org/10.1055/s-0030-1250094.

Chao, D.Y., Gable, K., Chen, M., Baxter, I., Dietrich, C.R., Cahoon, E.B., et al., 2011. Sphingolipids in the root play an important role in regulating the leaf ionome in *Arabidopsis thaliana*. Plant Cell 23 (3), 1061–1081. https://doi.org/10.1105/tpc.110.079095.

[ChEBI] Chemical Entities of Biological Interest, 2024. CHEBI:168758 - Ethyl 7-epi-12-hydroxyjasmonate glucoside. https://www.ebi.ac.uk/chebi/searchId.do?chebiId=168758 (Accessed 15 April 2024).

Colzi, I., Lastrucci, L., Rangoni, M., Coppi, A., Gonnelli, C., 2018. Using *Myriophyllum aquaticum* (Vell.) Verdc. to remove heavy metals from contaminated water: better dead or alive? J. Environ. Manag. 213, 320–328. https://doi.org/10.1016/j.jenvman.2018.02.074.

Cosio, C., 2020. Inorganic mercury and methyl-mercury uptake and effects in the aquatic plant *Elodea nuttallii*: a review of multi-omic data in the field and in controlled conditions. Appl. Sci. 10 (5), 1817. https://doi.org/10.3390/app10051817.

Crane, K., Kregting, L., Coughlan, N.E., Cuthbert, R.N., Ricciardi, A., MacIsaac, H.J., Dick, J.T.A., Reid, N., 2022. Abiotic and biotic correlates of the occurrence, extent and cover of invasive aquatic *Elodea nuttallii*. Freshw. Biol. 67 (9), 1559–1570. https://doi.org/10.1111/fwb.13960.

Cuthbert, R.N., Crane, K., Dick, J.T.A., Caffrey, J.M., MacIsaac, H.J., Coughlan, N.E., 2019. Die Hard: impact of aquatic disinfectants on the survival and viability of invasive *Elodea nuttallii*. Aquat. Bot. 154, 11–17. https://doi.org/10.1016/j.aquabot.2018.12.003.

Czatzkowska, M., Harnisz, M., Korzeniewska, E., Koniuszewska, I., 2020. Inhibitors of the methane fermentation process with particular emphasis on the microbiological aspect: a review. Energy Sci. Eng. 8 (5), 1880–1897. https://doi.org/10.1002/ese3.609.

Czerwińska, K., Śliz, M., Wilk, M., 2022. Hydrothermal carbonization process: fundamentals, main parameter characteristics and possible applications including an effective method of SARS-CoV-2 mitigation in sewage sludge. A review. Renew. Sustain. Energy Rev. 154, 111873 https://doi.org/10.1016/j.rser.2021.111873.

DellaGreca, M., Cutillo, F., D'Abrosca, B., Fiorentino, A., Pacifico, S., Zarrelli, A., 2009. Antioxidant and radical scavenging properties of *Malva sylvestris*. Nat. Prod. Commun. 4 (7), 893–896. https://doi.org/10.1177/1934578X0900400702.

Dembowska, E.A., Kamiński, D., Wojciechowska, A., 2021. Phytoplankton response to the massive expansion of *Elodea nuttallii* (Planch.) H. St. John, 1920 in a floodplain lake of the Vistula River (Poland). Aquat. Invasions 16 (4), 601–616. https://doi.org/10.3391/ai.2021.16.4.02.

Demirbaş, A., Arin, G., 2002. An overview of biomass pyrolysis. Energy Sources 24, 471–482. https://doi.org/10.1080/00908310252889979.

Di Nino, F., Thiébaut, G., Muller, S., 2005. Response of *Elodea nuttallii* (Planch.) H. St. John to manual harvesting in the north-east of France. Hydrobiologia 551, 147–157. https://doi.org/10.1007/s10750-005-4457-y.

Dorenbosch, M., Bakker, E.S., 2011. Herbivory in omnivorous fishes: effect of plant secondary metabolites and prey stoichiometry. Freshw. Biol. 56 (9), 1783–1797. https://doi.org/10.1111/j.1365-2427.2011.02618.x.

Dringenberg, H.C., Hargreaves, E.L., Baker, G.B., Cooley, R.K., Vanderwolf, C.H., 1995. p-Chlorophenylalanine-induced serotonin depletion: reduction in exploratory locomotion but no obvious sensory-motor deficits. Behav. Brain Res. 68 (2), 229–237. https://doi.org/10.1016/0166-4328(94)00174-e.

Duenas, M.A., 2022. *Elodea nuttallii* Nuttall's waterweed. CABI Compendium. https://doi.org/10.1079/cabicompendium.20761.

[EBA] European Biomass Association, 2022. Statistical report 2022. https://www.europeanbiogas.eu/_trashed-3/ (Accessed 15 April 2024).

Ekinci, K., Çiftçi, F., Kumbul, B.S., Yildirim, R., Solak, M., Çoban, V., 2023. Co-fermentation of macroalga *Elodea canadensis* in different mixing ratios with dairy manure. Biomass Conversion and Biorefinery 13 (15), 14185–14192. https://doi.org/10.1007/s13399-022-03587-7.

Emery-Butcher, H.E., Beatty, S.J., Robson, B.J., 2020. The impacts of invasive ecosystem engineers in freshwaters: a review. Freshw. Biol. 65, 999–1015. https://doi.org/10.1111/fwb.13479.

[EPPO] European and Mediterranean Plant Protection Organization, 2023. EPPO A1/A2 Lists of Pests Recommended for Regulation as Quarantine Pests (Accessed 15 April 2024).

European Commission, 2014. Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the Prevention and Management of the Introduction and Spread of Invasive Alien Species. European Union, Publications Office of the European Union, Luxembourg.

European Commission, 2017. Invasive Alien Species of Union Concern. European Union, Publications Office of the European Union, Luxembourg.

European Commission, 2019. Commission Implementing Regulation (EU) 2019/1262 of 25 July 2019 Amending Implementing Regulation (EU) 2016/1141 to Update the List of Invasive Alien Species of Union Concern. European Union, Publications Office of the European Union, Luxembourg.

Fujiwara, M., Koyama, M., Ban, S., Toda, T., 2020. Seasonal changes in the chemical composition and anaerobic digestibility of harvested submerged macrophytes. BioEnergy Research 13, 683–692. https://doi.org/10.1007/s12155-019-10082-x.

Fujiwara, M., Koyama, M., Akizuki, S., Ban, S., Toda, T., 2022. Influence of lignocellulosic components on the anaerobic digestibility of aquatic weeds: comparison with terrestrial crops. Ind. Crop. Prod. 178, 114576 https://doi.org/10.1016/j.indcrop.2022.114576.

Gacem, M.A., Gacem, H., Telli, A., El Hadj Khelil, A.O., 2020. Chapter 6 - mycotoxin-induced toxicities and diseases. In: Nanomycotoxicology. Academic Press, pp. 117–154. https://doi.org/10.1016/B978-0-12-817998-7.00006-9.

Gallegos, D., Wedwitschka, H., Möller, L., Weinrich, S., Zehnsdorf, A., Nelles, M., Stinner, W., 2018. Mixed silage of *Elodea* and wheat straw as a substrate for energy production in anaerobic digestion plants. Energy, Sustainability and Society 8 (1), 1–8. https://doi.org/10.1186/s13705-018-0148-1.

Gallegos-Ibanez, D., Jurado-Molina, J., Wedwitschka, H., Delgado, E., Nelles, M., Stinner, W., 2023. Ensiling of invasive *Elodea* sp., a novel aquatic biomass feedstock for the sustainable biogas production: effects of wheat straw and silage additives on silage quality and methane production. ACS Agricultural Science & Technology. https://doi.org/10.1021/acsagscitech.3c00043.

Garland, D., Earle, W., Caffrey, J., Taylor, C., Meehan, S., Touzet, N., Lucy, F., 2022. Management of the invasive nuttall's pondweed (*Elodea nuttallii*) in lough arrow, a Natura 2000 designated lake in western Ireland. Management of Biological Invasions 13 (1). https://doi.org/10.3391/mbi.2022.13.1.07.

Grigatti, M., Boanini, E., Cavani, L., Ciavatta, C., Marzadori, C., 2015. Phosphorus in digestate-based compost: chemical speciation and plant-availability. Waste Biomass Valor 6, 481–493. https://doi.org/10.1007/s12649-015-9383-2.

He, L., Bakker, E.S., Nunez, M.M.A., Hilt, S., 2019. Combined effects of shading and clipping on the invasive alien macrophyte *Elodea nuttallii*. Aquat. Bot. 154, 24–27. https://doi.org/10.1016/j.aquabot.2018.11.014.

Hegnauer, R., 1963. Chemotaxonomie der Pflanzen: eine Übersicht über die Verbreitung und die systematische Bedeutung der Pflanzenstoffe. Birkhäuser, Basel.

[HMDB] The Human Metabolome Database, 2024. Showing metabocard for lansioside C (HMDB0035103). https://hmdb.ca/metabolites/HMDB0035103 (Accessed 15 April 2024).

Hoffmann, M.A., González, A.B., Raeder, U., Melzer, A., 2013. Experimental weed control of *Najas marina* ssp. *intermedia* and *Elodea nuttallii* in lakes using biodegradable jute matting. J. Limnol. 72 (3) https://doi.org/10.4081/jlimnol.2013.e39.

Holmes, D.E., Smith, J.A., 2016. Chapter one - biologically produced methane as a renewable energy source. In: Sariaslani, S., Gadd, G.M. (Eds.), Advances in Applied Microbiology, vol. 97. Academic Press, pp. 1–61. https://doi.org/10.1016/bs.aambs.2016.09.00.

[IPBES] The Intergovernmental Science-Policy Platform on Biodiversity. https://www.ipbes.net/, 2023 (Accessed 15 April 2024).

[IUCN] International Union for Conservation of Nature, 2023. Invasive alien species. https://www.iucn.org/our-work/topic/invasive-alien-species. (Accessed 15 April 2024).

Iweh, N.S., Koyama, M., Akizuki, S., Ban, S., Toda, T., 2020. Novel wet-solid states serial anaerobic digestion process for enhancing methane recovery of aquatic plant biomass. Sci. Total Environ. 730, 138993 https://doi.org/10.1016/j.scitotenv.2020.138993.

Jones, C.G., Lawton, J.H., Shachak, M., 1994. Organisms as ecosystem engineers. Oikos 69 (3), 373–386. https://doi.org/10.2307/3545850.

Josefsson, M., 2011. Invasive species fact sheet – *Elodea canadensis, Elodea nuttallii* and *Elodea callitrichoides*. Online Database of the European Network on Invasive Alien Species – NOBANIS. www.nobanis.org. (Accessed 15 April 2024).

Kadono, Y., 2004. Alien aquatic plants naturalized in Japan: history and present status. Global Environ. Res. 8 (2), 163–169.

Kaur, M., Kumar, M., Sachdeva, S., Puri, S.K., 2018. Aquatic weeds as the next generation feedstock for sustainable bioenergy production. Bioresour. Technol. 251, 390–402. https://doi.org/10.1016/j.biortech.2017.11.082.

Kelly, R., Harrod, C., Maggs, C.A., Reid, N., 2015. Effects of *Elodea nuttallii* on temperate freshwater plants, microalgae and invertebrates: small differences between invaded and uninvaded areas. Biol. Invasions 17 (7), 2123–2138. https://doi.org/10.1007/s10530-015-0865-8.

Khan, Z., Nath, N., Rauf, A., Emran, T.B., Mitra, S., Islam, F., et al., 2022. Multifunctional roles and pharmacological potential of β-sitosterol: emerging evidence toward clinical applications. Chem. Biol. Interact., 110117 https://doi.org/10.1016/j.cbi.2022.110117.

Kim, S.Y., Yun-Choi, H.S., 2010. A comparative optical aggregometry study of antiplatelet activity of taxanes from *Taxus cuspidata*. Thromb. Res. 125 (6), e281–e284. https://doi.org/10.1016/j.thromres.2009.12.024.

Kim, M.G., Kim, S., Boo, K.H., Kim, J.H., Kim, C.S., 2024. Anti-inflammatory effects of immature *Citrus unshiu* fruit extracts via suppression of NF-κB and MAPK signal pathways in LPS-induced RAW264.7 macrophage cells. Food Sci. Biotechnol. 33, 903–911. https://doi.org/10.1007/s10068-023-01390-2.

Kolada, A.K., Pasztaleniec, A., Pasztaleniec, A., Bielczyńska, A., Kutyła, S., Kutyła, S., 2022. Taking over the dominance of the macrophyte community by *Elodea nuttallii* (Planch.) H. St. John is poorly reflected in ecological status assessment results. Aquat. Invasions 17 (4), 516–542.

Koyama, M., Yamamoto, S., Ishikawa, K., Ban, S., Toda, T., 2014. Anaerobic digestion of submerged macrophytes: chemical composition and anaerobic digestibility. Ecol. Eng. 69, 304–309. https://doi.org/10.1016/j.ecoleng.2014.05.013.

Kubo, I., Kinst-Hori, I., Yokokawa, Y., 1994. Tyrosinase inhibitors from *Anacardium occidentale* fruits. J. Nat. Prod. 57 (4), 545–551. https://doi.org/10.1021/np50106a021.

Kumar, G., Sharma, J., Goswami, R.K., Shrivastav, A.K., Tocher, D.R., Kumar, N., Chakrabarti, R., 2022. Freshwater macrophytes: a potential source of minerals and fatty acids for fish, poultry, and livestock. Front. Nutr. 9, 869425 https://doi.org/10.3389/fnut.2022.869425.

Kunii, H., 1984. Seasonal growth and profile structure development of *Elodea nuttallii* (Planch.) St. John in pond Ojaga-Ike, Japan. Aquat. Bot. 18 (3), 239–247. https://doi.org/10.1016/0304-3770(84)90065-2.

Labatut, R.A., Angenent, L.T., Scott, N.R., 2011. Biochemical methane potential and biodegradability of complex organic substrates. Bioresour. Technol. 102 (3), 2255–2264. https://doi.org/10.1016/j.biortech.2010.10.035.

Lengler, I., Buhrke, T., Scharmach, E., Lampen, A., 2012. In-vitro toxicological and proteomic analysis of furan fatty acids which are oxidative metabolites of conjugated linoleic acids. Lipids 47 (11), 1085–1097. https://10.1007/s11745-012-3713-y.

Liang, J.Y., Huang, K.S., Gunatilaka, A.A.L., Yang, L., 1998. 2-Deacetoxytaxinine B: a taxane diterpenoid from *Taxus chinensis*. Phytochemistry 47 (1), 69–72. https://doi.org/10.1016/S0031-9422(97)00515-3.

Liu, M., Saeki, K., Matsunobu, T., Okuno, T., Koga, T., Sugimoto, Y., et al., 2014. 12-Hydroxyheptadecatrienoic acid promotes epidermal wound healing by accelerating keratinocyte migration via the BLT2 receptor. J. Exp. Med. 2 (6), 1063–1078. https://10.1084/jem.20132063.

Macêdo, R.L., Haubrock, P.J., Klippel, G., Fernandez, R.D., Leroy, B., Angulo, E., et al., 2024. The economic costs of invasive aquatic plants: a global perspective on ecology and management gaps. Sci. Total Environ. 908, 168217 https://doi.org/10.1016/j.scitotenv.2023.168217.

Mazej Grudnik, Z., Germ, M., 2013. Spatial pattern of native species *Myriophyllum spicatum* and invasive alien species *Elodea nuttallii* after introduction of the latter one into the Drava River (Slovenia). Biologia 68, 202–209. https://doi.org/10.2478/s11756-013-0006-8.

Millane, M., Caffrey, J., O'Flynn, C., 2016. Risk Assessment of *Elodea nuttallii* – submission for consideration of Union listing under EU IAS Regulation No. 1143/2014. EU amended template for submission February. Version 1.2.1.

Miranda, A.F., Biswas, B., Ramkumar, N., Singh, R., Kumar, J., James, A., et al., 2016. Aquatic plant *Azolla* as the universal feedstock for biofuel production. Biotechnol. Biofuels 9, 1–17. https://doi.org/10.1186/s13068-016-0628-5.

Möller, L., Bauer, A., Wedwitschka, H., Stinner, W., Zehnsdorf, A., 2018. Crop characteristics of aquatic macrophytes for use as a substrate in anaerobic digestion plants—a study from Germany. Energies 11 (11), 3016. https://doi.org/10.3390/en11113016.

Möller, K., Schulz, R., Muller, T., 2010. Substrate inputs, nutrient flows and nitrogen loss of two centralized biogas plants in southern Germany. Nutrient Cycl. Agroecosyst. 87, 307–325. https://doi.org/10.1007/s10705-009-9340-1.

Mönchgesang, S., Strehmel, N., Schmidt, S., Westphal, L., Taruttis, F., Müller, E., Herklotz, S., Neumann, S., Scheel, D., 2016. Natural variation of root exudates in *Arabidopsis thaliana*-linking metabolomic and genomic data. Sci. Rep. 6 (1), 29033 https://doi.org/10.1038/srep29033.

Mubofu, E.B., Mgaya, J.E., 2018. Chemical valorization of cashew nutshell waste. Top. Curr. Chem. 376 (2), 8. https://doi.org/10.1007/s41061-017-0177-9.

Muñoz Escobar, M., Voyevoda, M., Fühner, C., Zehnsdorf, A., 2011. Potential uses of *Elodea nuttallii*-harvested biomass. Energy, Sustainability and Society 1, 1–8. https://doi.org/10.1186/2192-0567-1-4.

Naseem, S., Bhat, S.U., Gani, A., Bhat, F.A., 2021. Perspectives on utilization of macrophytes as feed ingredient for fish in future aquaculture. Rev. Aquacult. 13 (1), 282–300. https://doi.org/10.1111/raq.12475.

Nishizawa, M., Nishide, H., Kosela, S., Hayashi, Y., 1983. Structure of lansiosides: biologically active new triterpene glycosides from *Lansium domesticum*. J. Org. Chem. 48 (24), 4462–4466. https://doi.org/10.1021/jo00172a004.

Osama, M., Wei, C.L., Saleem, R., Unar, A.A., Unar, K., Siyal, K.J., et al., 2023. Aquatic plants with anti-inflammatory and anti-oxidant activities. Journal of Survey in Fisheries Sciences 10 (1), 3802–3806. https://doi.org/10.53555/sfs.v10i1.1738.

Pels, J.R., Blijendaal, L.P.J., Nijman, M.R.W., Zandvoort, M.H., Cieplik, M.K., 2014. Conversion of water plants to biomass fuel using TORWASH. In: 22nd European Biomass Conference and Exhibition, 23-26 June 2014, Hamburg, Germany.

Poerschmann, J., Weiner, B., Wedwitschka, H., Zehnsdorf, A., Koehler, R., Kopinke, F.D., 2015. Characterization of biochars and dissolved organic matter phases obtained upon hydrothermal carbonization of *Elodea nuttallii*. Bioresour. Technol. 189, 145–153. https://doi.org/10.1016/j.biortech.2015.03.146.

Preston, C.D., Croft, J.M., 2014. Aquatic Plants in Britain and Ireland. Harley Books for the Environmental Agency, Institute of Terrestrial Ecology and the Joint Nature Conservation Committee, Colchester, p. 365.

Rezq, S., Mahmoud, M.F., El-Shazly, A.M., El Raey, M.A., Sobeh, M., 2021. Anti-inflammatory, antipyretic, and analgesic properties of *Potamogeton perfoliatus* extract: in vitro and in vivo study. Molecules 26 (16), 4826. https://doi.org/10.3390/molecules26164826.

Ruan, T., Zeng, R., Yin, X.Y., Zhang, S.X., Yang, Z.H., 2016. Water hyacinth (*Eichhornia crassipes*) biomass as a biofuel feedstock by enzymatic hydrolysis. BioResources 11 (1), 2372–2380. https://doi.org/10.15376/biores.11.1.2372-2380.

Sabogal-Guáqueta, A.M., Villamil-Ortiz, J.G., Arias-Londoño, J.D., Cardona-Gómez, G.P., 2018. Inverse phosphatidylcholine/phosphatidylinositol levels as peripheral biomarkers and phosphatidylcholine/lysophosphatidylethanolamine-phosphatidylserine as hippocampal indicator of postischemic cognitive impairment in rats. Front. Neurosci. 21 (12), 989. https://doi.org/10.3389/fnins.2018.00989.

Schwoerer, T., Morton, J., 2018. Human dimensions of aquatic invasive species in Alaska: lessons learned while integrating economics, management, and biology to incentivize early detection and rapid response. In: Lewis, T. (Ed.), Alaska Economic, Environmental, and Social Issues. Nova Science Publishers, New York (Chapter 1).

Sciessere, L., Cunha-Santino, M.B., Bianchini Jr., I., 2011. Cellulase and xylanase activity during the decomposition of three aquatic macrophytes in a tropical oxbow lagoon. Br. J. Microbiol. 42, 909–918. https://doi.org/10.1590/S1517-83822011000300009.

Shepherd, T., Dobson, G., Verrall, S.R., Conner, S., Griffiths, D.W., McNicol, J.W., et al., 2007. Potato metabolomics by GC–MS: what are the limiting factors? Metabolomics 3 (4), 475–488. https://doi.org/10.1007/s11306-007-0058-2.

Shin, J.S., Hong, Y., Lee, H.H., Ryu, B., Cho, Y.W., Kim, N.J., et al., 2015. Fulgidic acid isolated from the rhizomes of *Cyperus rotundus* suppresses LPS-induced iNOS, COX-2, TNF-α, and IL-6 expression by AP-1 inactivation in RAW264.7 macrophages. Biol. Pharm. Bull. 38 (7), 1081–1086. doi:10.1248/bpb.b15-00186.

Shrestha, T.B., Chetri, S.K.K., Banskota, A.H., Manandhar, M.D., Taylor, W.C., 1997. 2-deacetoxytaxinine B: a new taxane from *Taxus wallichiana*. Journal of Natural Products 60 (8), 820–821. https://doi.org/10.1021/np9606153.

Simpson, D.A., 1984. A short history of the introduction and spread of *Elodea* Michx. the British Isles. Watsonia 15, 1–9.

Sivasankari, B., Ravindran, D., 2016. A study on chemical analysis of water hyacinth (*Eichornia crassipes*), water lettuce (*Pistia stratiotes*). Int. J. Innov. Res. Sci. Eng. Technol. 5 (10), 17566–17570. https://doi.org/10.15680/IJIRSET.2016.0510010.

Song, H., Wang, J., Garg, A., Lin, X., Zheng, Q., Sharm, S., 2019. Potential of novel biochars produced from invasive aquatic species outside food chain in removing ammonium nitrogen: comparison with conventional biochars and clinoptilolite. Sustainability 11 (24), 7136. https://doi.org/10.3390/su11247136.

Sopajarn, A., Sangwichien, C., 2015. Optimization of enzymatic saccharification of alkali pretreated *Typha angustifolia* for glucose production. Int. J. Chem. Eng. Appl. 6 (4), 232. https://doi.org/10.7763/IJCEA.2015.V6.487.

Stabenau, N., Zehnsdorf, A., Rönicke, H., Wedwitschk, H., Möller, L., Ibrahim, B., Stinner, W., 2018. A potential phosphorous fertilizer for organic farming: recovery of phosphorous resources in the course of bioenergy production through anaerobic digestion of aquatic macrophytes. Energy, Sustainability and Society 8 (1), 1–10. https://doi.org/10.1186/s13705-018-0155-2.

Steen, B., Cardoso, A.C., Tsiamis, K., Nieto, K., Engel, J., Gervasini, E., 2019. Modelling hot spot areas for the invasive alien plant *Elodea nuttallii* in the EU. Management of Biological Invasions 10 (1), 151–170. https://doi.org/10.3391/mbi.2019.10.1.10.

Strehmel, N., Böttcher, C., Schmidt, S., Scheel, D., 2014. Profiling of secondary metabolites in root exudates of *Arabidopsis thaliana*. Phytochemistry 108, 35–46. https://doi.org/10.1016/j.phytochem.2014.10.003.

Szabó, S., Scheffer, M., Roijackers, R., Waluto, B., Braun, M., Nagy, P.T., et al., 2010. Strong growth limitation of a floating plant (*Lemna gibba*) by the submerged macrophyte (*Elodea nuttallii*) under laboratory conditions. Freshw. Biol. 55 (3), 681–690. https://doi.org/10.1111/j.1365-2427.2009.02308.x.

Tang, Y., Qian, C., Zhao, L., Wang, C., Tang, B., Peng, X., et al., 2023. Comparative metabolomics analysis of *Elodea nuttallii* and *Cladophora* sp. in aquaculture systems. Aquaculture 563, 738950. https://doi.org/10.1016/j.aquaculture.2022.738950.

Tedesco, S., Stokes, J., 2017. Valorisation to biogas of macroalgal waste streams: a circular approach to bioproducts and bioenergy in Ireland. Chem. Pap. 71, 721–728. https://doi.org/10.1007/s11696-016-0005-7.

Tekin, K., Karagöz, S., Bektaş, S., 2014. A review of hydrothermal biomass processing. Renew. Sustain. Energy Rev. 40, 673–687. https://doi.org/10.1016/j.rser.2014.07.216.

Tori, M., Kawahara, M., Sono, M., 1998. Eremophilane-type sesquiterpenes from fresh rhizomes of *Petasites japonicus*. Phytochemistry 47 (3), 401–409. https://doi.org/10.1016/S0031-9422(97)00581-5.

Tuszynska, A., Czerwionka, K., Obarska-Pempkowiak, H., 2021. Phosphorus concentration and availability in raw organic waste and post fermentation products. J. Environ. Manag. 278, 111468 https://doi.org/10.1016/j.jenvman.2020.111468.

Ubando, A.T., Chen, W.H., Hurt, D.A., Conversion, A., Rajendran, S., Lin, S.L., 2022. Biohydrogen in a circular bioeconomy: a critical review. Bioresour. Technol. 366, 128168 https://doi.org/10.1016/j.biortech.2022.128168.

Unadkat, K., Parikh, P., 2021. Therapeutic potential of some aquatic macrophytes: an overview. Trends Med. Res. 16 (1), 1–6. https://doi.org/10.3923/tmr.2021.1.6.

Vanderstukken, M., Declerck, S.A., Decaestecker, E., Muylaert, K., 2014. Long-term allelopathic control of phytoplankton by the submerged macrophyte *Elodea nuttallii*. Freshw. Biol. 59 (5), 930–941. https://doi.org/10.1111/fwb.12316.

Vítěz, T., Koutný, T., Geršl, M., Kudělka, J., Nitayapat, N., Ryant, P., et al., 2015. Biogas and methane yield from rye grass. Acta Univ. Agric. Silvic. Mendelianae Brunensis 63, 143–146. https://doi.org/10.11118/actaun201563010143.

Wang, X.S., 2010. Invasive freshwater macrophyte alligator weed: novel adsorbent for removal of malachite green from aqueous solution. Water Air Soil Pollut. 206, 215–223. https://doi.org/10.1007/s11270-009-0097-6.

Wang, Z., Yun, S., Xu, H., Wang, C., Zhang, Y., Chen, J., Jia, B., 2019. Mesophilic anaerobic co-digestion of acorn slag waste with dairy manure in a batch digester: focusing on mixing ratios and bio-based carbon accelerants. Bioresour. Technol. 286, 121394 https://doi.org/10.1016/j.biortech.2019.121394.

Weinberg, Z.G., Ashbell, G., 2003. Engineering aspects of ensiling. Biochem. Eng. J. 13 (2–3), 181–188. https://doi.org/10.1016/S1369-703X(02)00130-4.

Wilt, T.J., MacDonald, R., Ishani, A., 1999. Beta-sitosterol for the treatment of benign prostatic hyperplasia: a systematic review. Br. J. Urol. 83 (9), 976–983. https://doi.org/10.1046/j.1464-410x.1999.00026.x.

Wishnek, B., Dlugolecki, L., 2020. Rapid Response Plan for *Elodea* in Alaska. United States Fish and Wildlife Service. Alaska Region, Anchorage, Alaska. https://www.fws.gov/media/rapid-response-plan-elodea-alaska-pdf. (Accessed 15 April 2024).

Wolff, P., 1980. Die hydrilleae (hydrocharitaceae) in europa [hydrilleae (hydrocharitaceae) in Europe]. Göttinger Floristische Rundbriefe 14, 33–56.

Wu, L., Han, G., Zhang, J., Wang, S., Qin, B., Kou, X., et al., 2023. Feeding effect of *Alternanthera philoxeroides* and *Elodea nuttallii* on crayfish (*Procambarus clarkii*) growth, hepatopancreas enzyme activity, and muscle quality. Aquacult. Int. 1–16. https://doi.org/10.1007/s10499-023-01156-x.

Xiao, L., Yang, L., Zhang, Y., Gu, Y., Jiang, L., Qin, B., 2009. Solid state fermentation of aquatic macrophytes for crude protein extraction. Ecol. Eng. 35 (11), 1668–1676. https://doi.org/10.1016/j.ecoleng.2008.08.004.

Xiong, H.F., 2019. Uptake kinetics of NH4+, NO3-and H2PO4-by submerged macrophytes *Elodea nuttallii* (St. John, 1920) and *Vallisneria natans* (Jussieu, 1826). Appl. Ecol. Environ. Res. 17 (1) https://doi.org/10.15666/aeer/1701_10271037.

Xu, L., Cheng, S., Zhuang, P., Xie, D., Li, S., Liu, D., et al., 2020. Assessment of the nutrient removal potential of floating native and exotic aquatic macrophytes cultured in swine manure wastewater. Int. J. Environ. Res. Publ. Health 17 (3), 1103. https://doi.org/10.3390/ijerph17031103.

Xu, J., Deshusses, M.A., 2015. Fermentation of swine wastewater-derived duckweed for biohydrogen production. Int. J. Hydrogen Energy 40 (22), 7028–7036. https://doi.org/10.1016/j.ijhydene.2015.03.166.

Xu, X., Zhou, Q., Yu, D., 2022. The future of hydrogen energy: bio-hydrogen production technology. Int. J. Hydrogen Energy 47, 33677–33698. https://doi.org/10.1016/j.ijhydene.2022.07.261.

Yoshikawa, M., Murakami, T., Shimada, H., Yoshizumi, S., Saka, M., Yamahara, J., Matsuda, H., 1998. Medicinal foodstuffs. XIV. On the bioactive constituents of moroheiya. (2): new fatty acids, corchorifatty acids A, B, C, D, E, and F, from the leaves of *Corchorus olitorius* L. (Tiliaceae): structures and inhibitory effect on NO production in mouse peritoneal macrophages. Chemical and Pharmaceutical Bulletin (Tokyo) 46 (6), 1008–1014. doi:10.1248/cpb.46.1008.

Zehnsdorf, A., Korn, U., Pröter, J., Naumann, D., Seirig, M., Rönicke, H., Pieper, B., 2011. Western waterweed (*Elodea nuttallii*) as a co-substrate for biogas plants. Landtechnik 66 (2), 136–139.

Zehnsdorf, A., Hussner, A., Eismann, F., Rönicke, H., Melzer, A., 2015. Management options of invasive *Elodea nuttallii* and *Elodea canadensis*. Limnologica 51, 110–117. https://doi.org/10.1016/j.limno.2014.12.010.

Zehnsdorf, A., Möller, L., Stärk, H.J., Auge, H., Röhl, M., Stinner, W., 2017. The study of the variability of biomass from plants of the Elodea genus from a river in Germany over a period of two hydrological years for investigating their suitability for biogas production. Energy, Sustainability and Society 7 (1), 1–7. https://doi.org/10.1186/s13705-017-0117-0.

Zehnsdorf, A., Möller, L., Stabenau, N., Bauer, A., Wedwitschka, H., Gallegos, W., Herbes, C., 2018. Biomass potential analysis of aquatic biomass and challenges for its use as a nonconventional substrate in anaerobic digestion plants. Eng. Life Sci. 18 (7), 492–497. https://doi.org/10.1002/elsc.201800032.

Zhang, Q., Hu, J., Lee, D.J., 2016. Biogas from anaerobic digestion processes: research updates. Renew. Energy 98, 108–119. https://doi.org/10.1016/j.renene.2016.02.029.

Zhang, B., Biswal, B.K., Zhang, J., Balasubramanian, R., 2023. Hydrothermal treatment of biomass feedstocks for sustainable production of chemicals, fuels, and materials: progress and perspectives. Chem. Rev. https://doi.org/10.1021/acs.chemrev.2c00673.

Zheng, Z., Nie, Z., Zheng, Y., Tang, X., Sun, Y., Zhu, H., et al., 2022. Effects of submerged macrophytes on the growth, morphology, nutritional value, and flavor of cultured largemouth bass (*Micropterus salmoides*). Molecules 27 (15), 4927. https://doi.org/10.3390/molecules27154927.

Zhou, J., Gao, J., Liu, Y., Ba, K., Chen, S., Zhang, R., 2012. Removal of fluoride from water by five submerged plants. Bull. Environ. Contam. Toxicol. 89, 395–399. https://doi.org/10.1007/s00128-012-0710-z.