

SHORT COMMUNICATION

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# Potential uses of *Elodea nuttallii*-harvested biomass

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## Abstract

*Elodea nuttallii* (PLANCH) St. John, an aquatic plant native to North America, shows invasive traits outside of its area of origin. In Europe, the plant has spread rapidly in water bodies. In Germany, the massive occurrence of *E. nuttallii* restricts recreational activities on lakes. Massive occurrences of *E. nuttallii* have been managed up to now by harvesting the plant and disposing of the biomass as organic waste, which results in high maintenance costs for lake administrators. Alternative uses to the disposal of the biomass were investigated. Analyzing the components and elemental composition of *E. nuttallii* samples from nine lakes in Germany, several potential uses were identified, such as the use of *E. nuttallii* biomass as a co-substrate with maize silage for biogas generation. Other potential applications, such as biochar production, soil amelioration, and energy recovery of feedstock chars in combustion plants, were identified from a hydrothermal carbonization process. The presence of  $\beta$ -sitosterol in *E. nuttallii*, which is used in the treatment of enlarged prostates, indicates a pharmaceutical use. Even though the elemental composition of *E. nuttallii* biomass contains the elements of a complete fertilizer, this particular use is not recommended given its slow decomposition in soil. The most feasible alternative identified was the use of *E. nuttallii* biomass as a co-substrate for biogas generation in combination with maize silage. The mixing of *E. nuttallii* with maize silage to facilitate storage and short distances between biogas plants and lakes with massive occurrence of *E. nuttallii* are important factors for its applicability.

**Keywords:** *Elodea nuttallii*, harvested biomass, potential uses

## Background

*Elodea nuttallii* (PLANCH) St. John is a fresh water aquatic plant native to temperate North America [1], which grows in lakes, ponds, canals, and slow-moving waters [2,3]. In the past, often confused with the well-known invasive water weed *Elodea canadensis*, *E. nuttallii* shows invasive traits where it has been introduced outside of its native area: rapid propagation and vegetative reproduction through fragments transported by water flows [2,4]. Its rapid propagation has even resulted in the displacement of *E. canadensis* [3,4]. According to Thiébaud [5], the introduction of non-native plants can lead to severe biological invasions; this description appears to apply to the spread of *E. nuttallii*.

Introduced into Europe in the first half of the twentieth century, *E. nuttallii* has been gaining attention due to its rapid spreading in European water bodies. *E.*

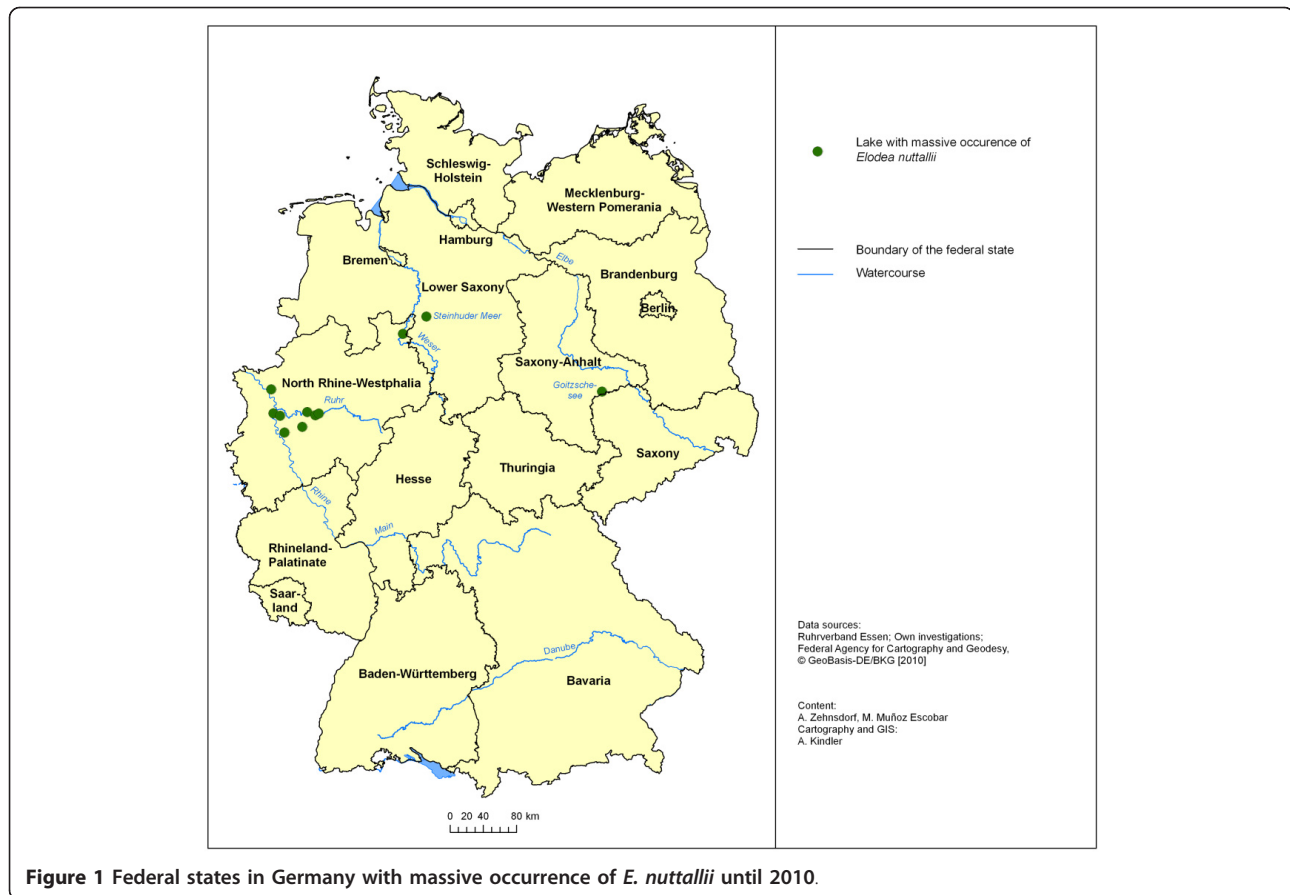
*nuttallii* was first reported in the Netherlands in 1941 [6], in France in the early 1950s [3], in Britain in 1966, and in Austria in 1977 [2]. Currently, it appears that *E. nuttallii* is actively spreading in many parts of Europe [3]. In Germany, the plant was first reported in 1953 in the Münster Botanical Garden of the Federal State of North Rhine-Westphalia [6]. Initially predominant in western Germany, the plant has now spread almost all over the country [7].

The federal states mostly affected by the massive occurrence of *E. nuttallii* are (see Figure 1): North Rhine-Westphalia (lakes: Hengstey, Harkort, Kemnader, Eyller, Kranenburger, Ville, Rees, Windheim, Wolfssee, Diersfelder Waldsee, Unterbacher, and Toeffpersee; dams: Neyetal and Lister dams), Lower Saxony (Steinhuder Meer lake) [8], and Saxony-Anhalt (Goitzsche lake) [9].

Apart from the negative impact on water quality as a consequence of the release of nutrients in a short period of time during autumn when the plants decay [10], the massive biomass produced by *E. nuttallii* also restricts

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**Figure 1** Federal states in Germany with massive occurrence of *E. nuttallii* until 2010.

water uses. Recreational activities on lakes are particularly affected by a massive occurrence of *E. nuttallii*; e.g., sailing, swimming, and surfing become either highly restricted or impossible [7,8].

There are several options for controlling overabundant aquatic plants; among them are biological and chemical control as well as manual and mechanical harvesting [3]. In Germany, mechanical harvesting is the option applied since the other alternatives are either forbidden (chemical control) or are not effective enough to control the massive occurrence of *E. nuttallii*.

The mechanical harvesting of *E. nuttallii* is a cost-intensive measure [7]. In addition to the harvesting costs, the administrators of the lakes have to pay for the disposal of *E. nuttallii* biomass, which is classified as an organic waste in Germany.

Research exploring alternatives to the disposal of the biomass as an organic waste which treats the biomass as a raw material for other uses could offer an insight into more sustainable strategies for maintaining lakes in good condition and ensuring their use for recreational activities at lower maintenance costs for the lake administrators.

Alternatives to the disposal of the biomass could be established investigating the various components of *E.*

*nuttallii*. In this paper, the results of research on the potential uses of *E. nuttallii* biomass as a co-substrate for the generation of biogas, for soil amendment after hydrothermal carbonization (HTC), for pharmaceutical extracts, and as a fertilizer are described.

## Materials and methods

### Samples

Fresh *E. nuttallii* biomass samples were collected from the following lakes in Germany: In North Rhine-Westphalia: Henne Dam (near Meschede) and Sorpe Dam (near Arnsberg) both located in the Homert Natural Park; Hengstey Lake (near Hagen), Kemnad Lake (near Bochum), Baldeney Lake (near Essen), Toepper Lake (near Duisburg). In Hesse: Perf Dam (near Marburg). In Lower Saxony: Lord lake (near Ankum). In Saxony-Anhalt: Goitzsche Lake (near Bitterfeld).

### Methods and instrumentation

#### Determination of biogas formation and methane yield of *E. nuttallii* samples

Samples of *E. nuttallii* from five lakes (Henne Dam, Baldeney Lake, Toepper Lake, Lord Lake, and Goitzsche Lake) were anaerobically digested in the laboratory

under static conditions using eudiometers. Anaerobic inoculum (250 g) were added to portions of plant material corresponding to 1 g of volatile solids and incubated in 500-mL glass bottles at 39°C for 40 days. The inoculum originated from the anaerobic stabilization of excess sludge from municipal sewage treatment, which had been pre-treated under anaerobic conditions for 3 weeks. An inoculum without *E. nuttallii* was incubated as a negative control. The positive controls contained 1 g of micro-crystalline cellulose. All tests except the *E. nuttallii* samples from Lake Lord were run in triplicates.

Moreover, in a pilot biogas reactor with a working volume of 40 L, maize silage was replaced step by step with *Elodea* of the harvested moisture content. The substituted amount of maize silage depended on the organic content and the oDM (i.e., the organic dry matter) of *Elodea*.

#### **Hydrothermal carbonization**

Hydrothermal carbonization (HTC) was carried out in a high-pressure laboratory autoclave (a 200-mL Model II from Carl Roth GmbH + Co KG, Karlsruhe, Germany). Air-dry *Elodea* was suspended with a mass ratio of 1:10 in a 0.01% (*w/w*) aqueous solution of citric acid and kept in the autoclave for 16 h at either 200°C or 240°C under autogenous pressures. After autoclaving, the suspensions were passed through 0.45- $\mu$ m cellulose acetate filters. Filter residues were dried at 105°C and weighted.

#### **Determination of organic substances in plant samples**

For the extraction procedure, 4 g of homogenized dry plant material was extracted by pressurized liquid extraction using an "ASE200" instrument (Dionex, Sunnyvale, CA, USA). The sample was filled into a 16  $\times$  77-mm extraction thimble (Schleicher and Schuell, Dassel, Germany) and transferred into an 11-mL stainless steel extraction cell. Cyclohexane and acetone at a ratio of 30:70 (*v/v*) were used as extraction solvents. A pressure of 10 MPa was applied for the static extraction at a temperature of 140°C for 15 min (2 cycles). The flush volume amounted to 50% of the extraction cell volume. The volumes of the resulting extracts were combined and evaporated to about 1 mL. Clean-up on alumina using cyclohexane as an eluent removed parts of the dark green matrix and, after evaporating to 1 mL, an aliquot of 1  $\mu$ L was used for the gas chromatography/mass spectroscopy (GC/MS) analysis.

GC/MS analysis was performed using a "TraceGC-Polaris Q" GC-ion trap mass spectrometer system (Axel Semrau, Spockhövel, Germany) equipped with a split/splitless injector. The temperature of the injector was set at 230°C and the temperature of the transfer line at 280°C. The sample was injected in splitless mode using a splitless time of 1 min. For GC separation, an HP 5MS capillary column (30 m, 0.25 mm i.d., 0.25- $\mu$ m

film) was applied using an oven heating program of: 60°C, 1 min; 15 grad/min to 280°C, 20 min. Helium was used as a carrier gas under constant flow conditions (1 mL/min). The solvent delay time was set to 6 min.

The mass spectrometer operated at electron impact ionization (70 eV) in full scan mode (mass range 50 to 550 mass units) to identify the plant ingredients. Selected ion monitoring mode determining the target ions of sitosterol (*m/z* 414, 396, 329, and 213) was applied for the quantification of this component. The limit of quantification was found to be 500 ng/mL *Elodea* extract matrix  $\pm$ 12% mean standard deviation.

$\beta$ -Sitosterol was obtained from Supelco (Bellefonte, PA, USA). Cyclohexane and acetone (HPLC grade) were purchased from Supelco (Darmstadt, Germany). A solution of  $\beta$ -sitosterol in cyclohexane (2  $\mu$ g/mL) was used to confirm the identification of  $\beta$ -sitosterol in the plant extracts.

#### **Determination of dry weight and volatile solids**

Fresh samples of *E. nuttallii* were weighed and dried at 105°C to determine the dry weight. The dried samples were treated at 550°C in a muffle furnace to determine the content of volatile solids.

#### **Determination of C, H, N, and O in sediment, plant samples, and solid HTC products**

The dried materials were incinerated in a pure oxygen atmosphere at 950°C using a TruSpec CHN elemental analyzer (LECO Corporation, St Joseph, MI, USA). The carbon-containing components were quantified by IR analysis. The nitrogen-containing components were reduced to nitrogen and were quantified with a thermal conductivity detector. Oxygen concentrations were calculated as the difference between the overall biomass. The results of the C/H/N-analyses and the elemental analyses are presented below.

#### **Determination of P in plant samples and solid HTC products**

The analysis of the phosphorus content in particulate matter was carried out as reported earlier [11]. Total phosphorus in the *Elodea* biomass and HTC materials was measured according to the German standard methods (DIN 38414). Solid-phase phosphorus was determined after oxidation by ammonium nitrate in a muffle furnace. Portions of 0.1 to 0.3 g of the annealed residue were mixed with 25 mL of 1 M HCl and heated for 15 min. After cooling, deionized water was added to the suspension. After the addition of p-nitrophenol to an aliquot of the product, the solution was titrated with NaOH to yellow. The solution was discolored by the addition of sulfuric acid. KMnO<sub>4</sub> solution and deionized water were added, resulting in a defined sample volume. The phosphorus concentration was determined photometrically by the addition of ascorbic acid and ammonium molybdate at 880 nm.

### Determination of metals in plant samples and solid HTC products

The plant samples and solid HTC products were dried and ground. Portions of 0.45 g of the powder were mixed with 5 mL of 65% HNO<sub>3</sub> (suprapur, Merck, KGaA, Darmstadt, Germany) and 0.1 mL of 30% H<sub>2</sub>O<sub>2</sub> (suprapur, Merck). The mixtures were heated under pressure in an “UltraClave II” (MLS, Leutkirch, Germany) according to the following microwave oven program: 20°C to 200°C for 15 min, 200°C to 250°C for 10 min, 250°C hold for 15 min, cool down. The products were diluted to a volume of 50 mL with deionized water (MilliQ-Element/Millipore). The resulting samples were analyzed by means of inductively coupled plasma mass spectrometry using an Elan DRC-e (Perkin Elmer Corp., Waltham, MA, USA) following a 1:10 dilution with 0.5% (v/v) HNO<sub>3</sub> (ultrapur, Merck). The following isotopes were used for the measurements: 51-V; 52-Cr (using dynamic reaction cell (DRC) and methane as a reaction gas); 59-Co; 60-Ni; 75-As (using DRC with O<sub>2</sub> as a reaction gas: measuring 91-(AsO+)); 85-Rb; 90-Zr; 118-Sn; and  $\Sigma$ 206-, 207-, and 208-Pb. The interferences of Ca on 60-Ni and of Cl on 51-V were corrected for using an equation. The interferences on 52-Cr and 75-As were taken into account by applying dynamic reaction cell technology. All measured concentrations were well above the limits of quantification.

## Results and discussion

### *E. nuttallii* as a co-substrate for biogas plants

The results of anaerobic digestion of *E. nuttallii* biomass from the five different lakes under static conditions in the laboratory showed a similar yield of biogas (see Table 1). These results demonstrate the independence of the biogas yield with respect to the site of biomass origin. With an average of 450 standard liters (SL)/kg<sub>oDM</sub>, the yield of biogas from *E. nuttallii* is within the average of biogas yields obtained from maize silage of 650 SL/kg<sub>oDM</sub> [12], indicating a good potential for the use of the *E. nuttallii* biomass for biogas generation.

Nonetheless, the biogas generation related to fresh mass can be seen to be lower for *E. nuttallii* biomass (see Table 1), with 29 SL/kg<sub>FM</sub> compared to 200 SL/

kg<sub>FM</sub> of maize silage. The high content of water in *E. nuttallii* fresh biomass accounts for this lower value of biogas generation. While wilting the biomass straight after harvesting, up to 90% of the water content can be removed [13].

The digestion of *E. nuttallii* fresh mass as a single substrate in a laboratory reactor under continuous processing led to a reduction of more than 50% in the biogas yield. In order to test the potential of the use of *E. nuttallii* biomass as a co-substrate for biogas generation, additional experiments were carried out by gradually replacing maize silage with *E. nuttallii* biomass characterized by the harvested moisture content. The amount replaced was based on the organic dry matter values (oDM).

It was demonstrated that biogas generation with 100% *E. nuttallii* biomass is possible, though economically not viable. Figure 2 presents the results for the various mixtures, showing a decrease in the biogas yield when *E. nuttallii* biomass was added. One of the reasons for this decrease is the shorter residence time of *E. nuttallii* due to the lower organic dry matter content compared to maize silage, and the high content of water [13]. The mixture of 30% *E. nuttallii* biomass with 70% maize silage generated a biogas yield of 580 SL/kg<sub>oDM</sub>, which remains within the range of biogas yields from maize silage.

Furthermore, an addition of trace elements for process stabilization is needed for the generation of biogas. The use of *E. nuttallii* biomass for biogas generation can offer additional benefits for the process due to the presence of trace elements.

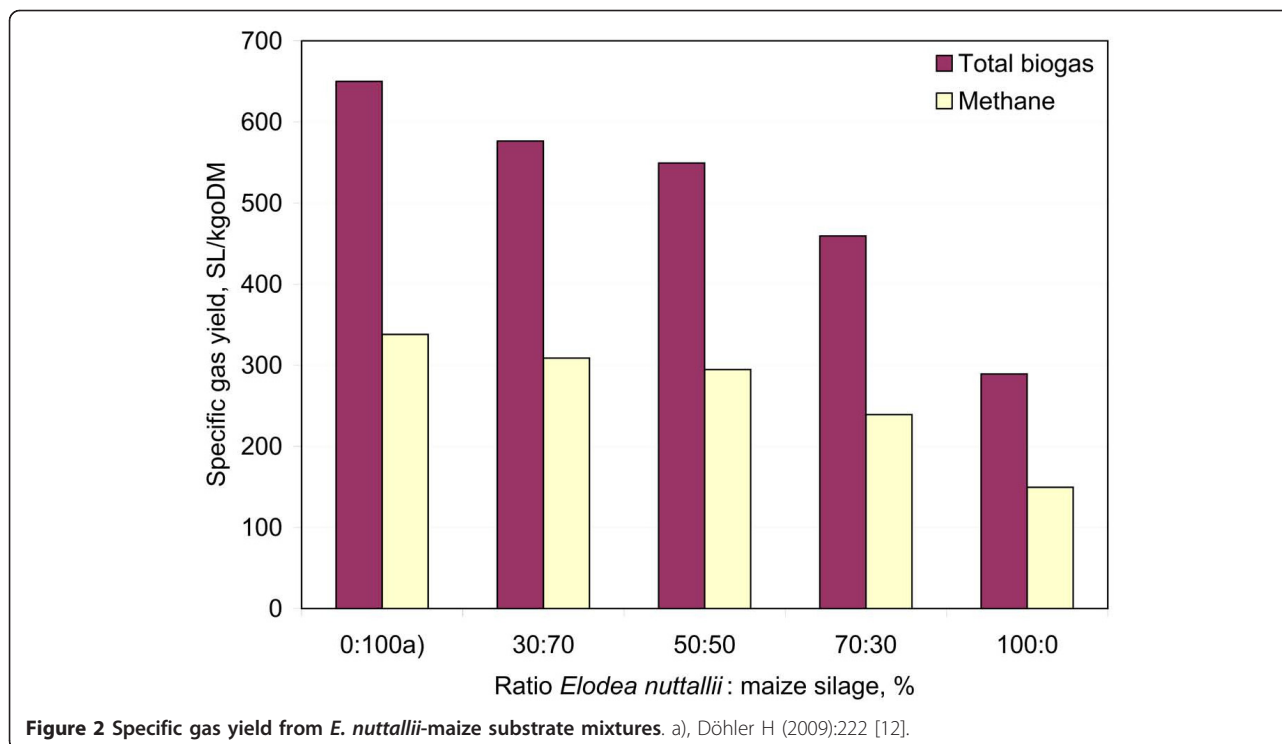
In regards to the use of *E. nuttallii* biomass as a co-substrate for biogas generation, one of the issues to be resolved is biomass storage. Biomass to be used for this purpose should be available for a long period of time. However, freshly harvested *E. nuttallii* biomass decomposes quickly and generates a strong putrid smell.

Zehnsdorf et al. [13] reported a good silage quality for a mixture of 30% pre-wilted *E. nuttallii* biomass and 70% maize, generating a biogas yield of 694 SL/kg<sub>oDM</sub> in laboratory experiments. At this mixture ratio with

**Table 1 Analysis of *E. nuttallii* samples from five lakes in Germany (n = 3)**

	DM (% in FM)	oDM (% in FM)	Gas formation(SL/kg <sub>oDM</sub> )	Gas formation(SL/kg <sub>FM</sub> )	CH <sub>4</sub> (%)
Baldeney Lake Essen	16.67	7.18	416	29.8	63
Goitzsche Lake Bitterfeld	6.74	4.36	476	20.6	55
Hennetal Dam Meschede	24.98	6.32	457	28.9	62
Lord Lake Osnabrück	6.33	4.82	415	20.0	64
Toepper Lake Duisburg	11.64	8.54	520	44.4	58

DM, dry matter; FM, in fresh mass; oDM, organic dry matter; SL/kg<sub>oDM</sub>, standard liters per kilogram of organic dry matter; SL/kg<sub>FM</sub>, standard liters per kilogram of fresh mass; CH<sub>4</sub>, methane.



maize, it is feasible to store *E. nuttallii* biomass that delivers a good performance in regards to biogas yield.

One condition for the feasibility of this alternative is a short distance between the locations of biomass harvesting and the biogas plants in order to avoid high transportation costs. In Germany, this condition is fulfilled since there are a large number of biogas plants close to the places of massive occurrences of *E. nuttallii* [7].

#### Hydrothermal carbonization

HTC is a process for the thermochemical conversion of carbonaceous materials in the presence of excess water at temperatures of  $>180^{\circ}\text{C}$  and autogenous pressures of  $>1.0\text{ MPa}$  for periods of several hours to days [14,15]. HTC and HTC-related processes with milder temperature/pressure regimes and shorter residence times can mainly be used for the carbonization and stabilization or the disintegration of water-rich biomass.

In the field of wastewater treatment, thermo-pressure technologies such as the CAMBI process (CAMBI, Asker, Norway) [16], are focused on increasing the dewaterability and digestibility of sewage sludges by cytolysis and the disruption of colloidal structures [17,18]. In addition, hydrothermal pretreatment can reduce foam formation in digestion processes [19]. Most studies on thermo-pressure-based methods for sewage sludge disintegration reported an optimal temperature range of  $160^{\circ}\text{C}$  to  $180^{\circ}\text{C}$  and treatment times of 30 to 60 min [18]. Exposure to higher temperatures can

decrease the biodegradability of certain fractions of the feedstock due to the formation of refractory substances [20].

In contrast to the application of thermal hydrolysis for sewage sludge disintegration, the formation of recalcitrant products is one of the main goals when applying the more severe conditions of HTC. While mass yields often decrease, the relative carbon content of solid HTC products usually increases with the temperature and residence time of the conversion process [15,21]. Dehydration, decarboxylation, demethanation, and reactions of secondary polymerization that take place at temperatures  $>170^{\circ}\text{C}$  lead to the formation of lignite-like materials with decreased O/C and H/C ratios and increased heating values. The generation of polycondensed aromatic structures is assumed to be responsible for the recalcitrance of pyrolyzed materials to microbial degradation [22]. Similar substances are most probably also generated in the course of HTC.

Against this background, there exists an increasing interest in HTC with regard to the use of its solid conversion products for soil carbon sequestration and soil amelioration [15,23], on the one hand, or as a renewable fuel with an increased calorific value [15,22], on the other. Compared to pyrolysis-based systems, HTC strategies are expected to be energetically advantageous for wet and moist feedstocks, as they allow for char production without predrying and for concomitant improvements of the mechanical dewaterability of the biomass.

Since the water-rich biomass of *E. nuttallii* does not face any relevant competition from alternative utilization routes, HTC with its multiple options for the integration into energy and material recovery systems appears to be particularly suitable for this material.

The first 16 h-experiments in our study regarding the HTC of *Elodea* biomass at 200°C and 240°C resulted in 65% and 59.5% of solid conversion products on a weight basis (Table 2). These char yields are in the range of values given by other authors [21]. Tsukashi [24], for example, obtained mass yields of 66% and 56% for wood that was treated for 72 h at 200°C and 250°C, respectively. At the same time, as the char yields of *Elodea* decreased, the concentrations of ash elements in the dry mass increased from 16.3% to 29.9% and 36.1%. In terms of the potential use of HTC chars for soil amelioration, the allocation of plant nutrient elements to the solid, liquid, and gaseous HTC products is of particular interest. When the HTC temperature was increased, the amount of major plant nutrients in the char decreased to different extents (Table 2). While on average 85% of K and 69% of N were removed from the particulate fraction, only around 20% of Mg and 10% of P were dissolved in the process waters. Faced with the high concentration of dissolved plant nutrients, such as K and N, future work has to develop strategies for an efficient treatment of process waters and recycling of nutrients in plant available speciations.

Elemental analyses showed an unexpectedly low C concentration in the *Elodea* biomass (Table 2). In addition, the tentative experiments in this study did not establish the relative accumulation of C and the decrease of the molar O/C ratio that is usually caused by dehydration and decarboxylation reactions in HTC processes [21]. Thus, even if the H/C values of the feedstock and their decline in the chars matched those obtained in other studies [21], the results of the C and H analyses as well as the calculated values of the oxygen

concentrations should have to be verified by more comprehensive work. In order to balance the suitability of hydrothermal processes for energy recovery of *Elodea* biomass and/or its recycling according to the biochar concept, detailed investigations of the conversion processes and their liquid and solid conversion products should be performed in the future.

#### Potential use of *E. nuttallii* biomass for pharmaceutical extracts

The medical use of *E. nuttallii* in its area of origin by indigenous cultures provides initial indications of the potential use of the plant for medical or cosmetic purposes. However, the results of a study of a large ethnic group settled around the Great Lakes of North America showed that unlike with *E. canadensis* and *E. potamogeton*, there are no references to the use of *E. nuttallii* (Schröder 2009, unpublished observations). According to Hegnauer [25], *E. nuttallii* does not contain any toxic or bitter components.

From the determination of organic substances in *E. nuttallii* in this research, it was established that there is a content of up to 462 ppm of  $\beta$ -sitosterol in the plant. This substance is applied in the medical treatment of enlarged prostates and prostate hyperplasia [26-28].

The concentration of  $\beta$ -sitosterol in *E. nuttallii* is lower than that found in other plants such as sage (*Salvia officinalis*), 2,450 ppm in leaves, hawthorn (*Crataegus laevigata*), 5,100 to 6,200 ppm in leaves, and basil (*Ocimum basilicum* L.), 896 to 1,705 ppm in leaves [29]. The extraction of  $\beta$ -sitosterol from *E. nuttallii* would therefore appear not to offer good prospects.

#### Potential use of *E. nuttallii* as a fertilizer

The elemental composition drawn from dry matter of *E. nuttallii* showed a relative average composition of nitrogen (N) 2.8%  $\pm$  0.7%, phosphorous (P) 0.4%  $\pm$  0.18%, and potassium (K) 2.9%  $\pm$  1.1%. Moreover, other main elements were found in the following percentages: magnesium (Mg) 0.24%  $\pm$  0.06%, calcium (Ca) 5.3%  $\pm$  3.1%, iron (Fe) 0.37%  $\pm$  0.21%, and sulfur (S) 0.26%  $\pm$  0.2%. The trace elements cobalt (Co) 11 ppm, copper (Cu) 26 ppm, and zinc (Zn) 305 ppm were also identified.

The composition of *E. nuttallii* biomass contains therefore the elements of a complete fertilizer (NPK) and other important elements for plant growth. The potential for using the biomass as an organic fertilizer is therefore confirmed from the point of view of the elemental composition. However, composting tests showed a slow degradation of the biomass in the soil, with decomposition taking years due to the high content of cellulose [8,18,19]. Further research regarding the cell structure of the plant is needed to identify potential

**Table 2 Mass yields and elemental composition of biomass and solid HTC products (HTC chars) of *E. nuttallii***

		HTC	HTC 200°C/16 h	HTC 240°C/16 h
Mass yield	(% w/w) <sup>a</sup>	-	65.0	59.5
C	(% w/w)	25.9	23.9	19.4
O	(% w/w)	50.8	41.5	40.9
H	(% w/w)	3.45	2.36	1.58
N	(% w/w)	2.25	1.24	1.01
K	(% w/w)	2.95	0.64	0.23
Mg	(% w/w)	0.19	0.16	0.15
P	(% w/w)	0.17	0.16	0.14
H/C	(mol/mol)	1.60	1.19	0.98
O/C	(mol/mol)	1.47	1.31	1.58

<sup>a</sup>Weight percent of dry matter.

uses derived from the content of cellulose in the biomass.

The rich elemental composition of *E. nuttallii* associated with its high capacity for nutrient uptake [30,31] can generate water quality problems due to the release of nutrients in autumn when the plants decay [10]. By periodically harvesting the plant, these nutrients are extracted from the water, thus controlling eutrophication and quality problems.

## Conclusions

In this paper, several options for the use of *E. nuttallii* biomass as alternatives to the disposal as organic waste were reviewed. Investigating the substances and elemental composition of the plant allows users to determine its potential for biogas generation and pharmaceutical application. However, the use as an organic fertilizer is not recommended.

*E. nuttallii* biomass can be employed as a co-substrate for biogas generation. The biogas yield of the biomass based on the organic dry matter is within the range of biogas yields obtained from maize silage. The high water content of the harvested biomass and problems with storage can be solved by producing a silage with a mixture of 30% pre-wilted *E. nuttallii* biomass and 70% maize. This mixture has a higher biogas yield than *E. nuttallii* biomass alone. The use of *E. nuttallii* biomass could be beneficial for biogas production since it contains the trace elements needed for the stabilization of the process. Short distances are desirable as regards the transportation of biomass to biogas plants, which is the case in Germany. These results show that the potential use of *E. nuttallii* biomass as a co-substrate for biogas generation is one of the most feasible applications among those described in this paper. Further experiments on the practicality of this application of *E. nuttallii* biomass in real-scale biogas plants are needed.

HTC and hydrothermal technologies for biomass disintegration have the potential to deliver sustainable material and/or energy recovery of *E. nuttallii* biomass. In principle, the high water contents of hydrophytes fulfill the prerequisites for running these processes. Conceptually, the reactions taking place during HTC increase the metabolic recalcitrance and the calorific value of carbonaceous feedstocks. HTC strategies could therefore be suitable for both the use of *E. nuttallii* in biochar-related concepts of carbon sequestration and soil amelioration as well as for the energy recovery of the feedstock chars in combustion plants. Even under milder temperature/pressure conditions and at shorter treatment times than typical for HTC, the hydrothermal treatment is accompanied by the disintegration of biomass. The cytolysis and disruption of colloidal structures not only improves the digestability of the feedstock but also its dewaterability.

Thus, thermo-pressure pretreatment could also be a valuable tool for the use of *Elodea* in biogas plants. Though our work has not been able to demonstrate effective carbonization as yet, HTC would appear to be applicable for the conversion of *Elodea* biomass in principle. More detailed studies have to be performed on hydrothermal conversion technologies and the characteristics of their products to judge the applicability of the concepts presented here for the recovery of *E. nuttallii* in practice. In particular, HTC products and those of related technologies such as the CAMBI process for sewage sludge treatment have not been investigated sufficiently thus far with regard to their value for soil amelioration and carbon sequestration.

The determination of the concentration of  $\beta$ -sitosterol in *E. nuttallii* biomass demonstrates its potential application as a raw material for the extraction of this substance that is used for the medical treatment of hyperplasia. Although the concentration of  $\beta$ -sitosterol found in *E. nuttallii* is lower than that found in other plants, it is important to consider that, once harvested, *E. nuttallii* biomass is a raw material available without extra production costs - an aspect that might make it an attractive source of  $\beta$ -sitosterol.

Even though the elemental composition of *E. nuttallii* biomass contains the basic nutrients for a complete fertilizer as well as trace elements, the use of the biomass as an organic fertilizer is not to be recommended due to its slow decomposition in soil. Further research regarding potential applications derived from the high content of cellulose (responsible for the slow decomposition of the biomass in the soil) and the extraction of nutrients for the production of inorganic fertilizer is needed.

The feasibility of alternative applications of *E. nuttallii* biomass should be assessed for each particular case. Whether the biomass is to be disposed of as an organic waste or can be used for one of the alternatives presented in this paper is ultimately an economic decision.

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#### Authors' contributions

MME evaluated the potential for exploitation of *E. nuttallii* and drafted the manuscript. MV carried out the chemical analyses. CF investigated the possibility of the use of *E. nuttallii* for hydrothermal carbonization. AZ conducted the field studies and coordinated the investigations. All authors read and approved the final manuscript.

#### Competing interests

The authors declare that they have no competing interests.

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