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Research Article

Biomass potential analysis of aquatic biomass and challenges for its use as a nonconventional substrate in anaerobic digestion plants

Aquatic macrophytes are important components of aquatic habitats. However, the overgrowth of aquatic plants can cause severe problems for the management of bodies of water. As a result, these plants must be removed and disposed of as waste. However, the usage of this biomass as a substrate in biogas plants would appear to be more beneficial. The present study shows the advantages and barriers to the use of harvested aquatic biomass for energy production in Germany. The results cover several aspects of this issue, such as the question of biomass potential, the quality of the harvested aquatic plants, and ensiling for the purpose of conservation for anaerobic digestion. In addition, the social aspects of the de-weeding in bodies of water are discussed.

Keywords: Anaerobic digestion / Aquatic macrophytes / Biogas / Biogas plants / Substrate

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1 Introduction

Submerge aquatic plants play a key role in the functioning of aquatic ecosystems. However, nuisance growth of submerged aquatic plants can cause problems for the human use of bodies of water [1]. Neophytes are aquatic plant species that can alter the composition of macrophyte communities in bodies of water through the formation of massive populations [2, 3]. The two *Elodea* species of *E. canadensis* and *E. nuttallii* have attracted considerable scientific and public interest due to their rapid spreading in Europe, Asia, and Australia. The uses of bodies of water—including the aspects of energy production, boat traffic, nature conservation and recovery, and swimming and leisure—can be strongly influenced by extensive biomass growth of *E. nuttallii*. The only current management method for mass stocks of *E. nuttallii* in Germany is de-weeding using mow-

ing boats [4] and composting the resulting aquatic biomass. However, composting of this wet biomass with a narrow carbon–nitrogen ratio (C/N) without lots of wood as a structural material results in a high risk of greenhouse gas emissions, especially CH₄, N₂O, and the indirect greenhouse gas NH₃.

Furthermore, the energetic value of this biomass remains unused while biogas plant operators are looking into ways to replace energy crops with input material that does not cause food versus fuel competition. Biogas production instead of disposing of this material would combine energy production and the reduction of costs and legitimacy pressures [1] for biogas plants with the reduction of greenhouse gas emissions and the improvement of nutrient cycles.

However, to make efficient use of aquatic plant biomass in biogas plants, it is necessary to know:

- (1) How much of this type of biomass is currently being harvested per year?
- (2) What is the quality of this biomass, including its biogas potential?
- (3) How can the biomass be stored after harvesting for use as a continuous substrate for biogas plants?
- (4) How do stakeholders in the body of water react to de-weeding and what conflicts can be anticipated?

In addition, a robust value chain has to be built involving technologies that allow for cost-effective use of aquatic biomass

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Abbreviations: C/N, carbon–nitrogen ratio; DM, dry matter; FM, fresh matter; oDM, organic dry matter; TS, total solid; VS, volatile solid

Compiled in honour of the 80th birthday of Professor Wolfgang Babel.

in biogas plants. We will touch upon this aspect only briefly in this discussion.

Little research has been carried out so far on the use of aquatic macrophytes in biogas plants. The amount of potentially usable aquatic biomass in Germany has not yet been estimated. Up to now, potential analyses have been restricted to very limited areas within the framework of upcoming maintenance measures. A comprehensive study in this regard for the maintenance of bodies of water was carried out as part of the AquaMak research project [5]. However, this data were voluntary and related only to aquatic biomass actually harvested. The quality of aquatic biomass harvested from inland waters in Germany under real conditions has not been investigated so far.

Conflicts in the area of nature conservation and use of the natural environment have been examined in numerous studies [6], but most researchers focus on how the activities of specific stakeholders impede nature conservation. An increasing number of publications describe how stakeholders can be integrated into planning processes and some also analyze stakeholder positions [7–9]. To our knowledge, no stakeholder analyses with regard to de-weeding have been performed so far.

Thus, the aim of this research was to address the four research questions listed above, focusing on the biomass of the aquatic plant genera *Elodea* and *Myriophyllum*.

2 Materials and methods

2.1 Biomass potential determination

2.1.1 Determination of area yields for aquatic plant biomass originating from standing waters

Three lakes—“Cospudener See” (51° 15' 59.5"N, 12° 20' 18.8" E), “Seelhausener See” (51° 35' 10.8" N, 12° 25' 44.39" E), and “Heider Bergsee” (50° 49' 48.3" N 6° 51' 58.5" E)—were examined over the time period between August 24 and September 24, 2016 in order to calculate the usable biomass potential of aquatic plants in standing waters in Germany. For the determination of the depth-dependent average area yield of the aquatic plant genera *Elodea* and *Myriophyllum*—which often occur in significant amounts in lakes—the help of divers was used. The harvest was carried out at water depths of 2, 4, and 6 m. In these tests, one square meter was completely harvested in three repetitions. The fresh matter (FM), the dry matter content and the organic matter content were determined on the day of harvesting.

In “Cospudener See” (Leipzig), the area with area-wide growth for aquatic plants in the shore area with a water depth of 0–5 m was determined. Up to a maximum depth of 2.5 m, *M. heterophyllum* was found together with *E. nuttallii*, followed by extensive *E. nuttallii* stocks up to a maximum depth of 6 m. On July 19, 2016, selected sections of “Cospudener See” were navigated by boat to estimate the aquatic plant population.

2.1.2 Determination of dry matter and organic dry matter content

The fresh samples of plants were weighed using a luggage scales on the bank directly after harvesting to determine the FM. After

being transported to the laboratory, the samples were dried at 105°C to determine their dry matter (DM). An aliquot of the dried samples was heated to 550°C in a muffle furnace to determine the content of organic DM (oDM) according to DIN 12879.

2.1.3 Determination of watershed areas

Apart from the area yields of the aquatic plants, the relevant water surfaces had to be determined to calculate the potential of the aquatic plant biomass. The usable potential (commercially available harvest boats can only harvest up to about 2 m of water depth) requires knowledge of the water surface with a water depth of 0–2 m. Since corresponding basic data are not available for all 15 657 stagnant waters in Germany, this determination was carried out on the basis of data for 695 lakes in the German federal state of Mecklenburg-Vorpommern. The source of this data was the depth information for these lakes in GeoPortal.MV (www.geoportal-mv.de), which can be accessed with the GAIA-MVprofessional Viewer. All lakes with a size of greater than 4 ha were selected and their depth profile was transferred to ARGGIS as a shape file. Subsequently, the total water surface and the water surface with a water depth of 0–2 m were determined for each lake.

2.2 Determination of biomass quality

2.2.1 Obtaining the aquatic plant biomass to be investigated

In order to assess the quality of aquatic plant biomass obtained in water conservation in Germany, harvested material from a total of 35 sites was examined in autumn 2015 and summer 2016. The delivery of 2–6 kg of freshly harvested aquatic plant biomass was carried out in well-sealed plastic buckets by post. The transport of the aquatic plant crop took place within the week in sealed plastic bags and additionally in tightly closed plastic buckets. The transport took a maximum of 2 days. Only one sample had to be discarded because of longer transport duration due to a holiday. Immediately after arriving, the samples were processed further. After the samples arrived at the laboratory, the aquatic plant species were determined. The plant samples were placed on a sieve with a mesh size of 5 mm, washed with tap water, and the sediment content in the wash water was then determined.

2.2.2 Determination of the C/N

To determine the concentrations of carbon and nitrogen in the plant samples, the aliquots were incinerated at 950°C in an element analyzer (Vario-EL III, Elementar Analysensysteme GmbH, Hanau, Germany) with a thermal conductivity detector. The C/N was then calculated from the determined carbon and nitrogen contents.

2.2.3 Storage of aquatic plant biomass

Ensiling was conducted on a laboratory scale by means of ensiling fermentation as previously described by Gallegos et al. [10].

Silages of fresh *Elodea* plant material and mixed silages of *Elodea* and chopped and ground straw at 30 and 45% total solids (TS) were tested. In addition, chemical, enzymatic, and biological silage additives were used individually or in combination to compare their mode of action. Storage was carried out under anaerobic conditions. The storage duration was 180 days and the experiments were performed in triplicate in order to ensure reproducibility.

2.2.4 Determination of methane potential

Biochemical methane potential (BMP) tests on a laboratory scale were conducted in accordance with VDI 4630 [11] using eudiometer devices (Neubert Glas GbR, Geschwenda, Germany) to determine the specific methane yields of the ensiled material after 180 days of storage. The samples consisted of 450 g of inoculum and approximately 2.5 g of volatile solids (VS) of the substrate, each in three replications. The inoculum to substrate rate was approximately 2.3:1. In addition to the sample materials, pure inoculum was tested to determine its methane yield in order to subtract this from the sample methane production. To monitor the inoculum performance, microcrystalline cellulose was used as a reference substrate. The inoculum was derived from the DBFZ research biogas plant. The substrates used in this research biogas plant were maize silage and cattle manure. The organic loading rate of the digestion process was 2.7 g VS/(L/day) and the hydraulic retention time was 103 days. Digestate from the primary digester was sieved (5 mm), diluted with tap water, and degassed at room temperature for 5 days to reduce the specific biogas generation prior BMP tests. The average chemical characteristics of the inoculum were pH 7.62, TS 1.62, VS 80.2%, $\text{NH}_4\text{-N}$ 1.34 g/L, and organic acids 53.01 mg/L.

The headspace of the test setup was flushed with nitrogen. Headspace correction was carried out as described in the method description in VDI 4630 [11]. The test was operated under mesophilic conditions (38°C) and was stirred once a day. The gas composition was determined using a land fill gas monitor (GA2000: Ansyco, Karlsruhe, Germany). The BMP test was ended when the daily biogas production had reduced to 1% of the total biogas production over a period of five consecutive days. The specific methane yields were standardized to 273.15 K and 1.01325×10^5 Pa.

2.3 Social aspects

A multi-method approach was used to detect conflicts in de-weeding of bodies of water. This started with an e-mail survey (see above), followed by a study of media reports on conflicts relating to de-weeding that yielded nearly 100 relevant articles, and finally six case studies were conducted based on 24 qualitative problem-centered interviews [12]. The data were analyzed using thematic qualitative text analysis [13, 14]. On the basis of these results, a stakeholder dialogue workshop was held in order to triangulate the positions and conflicts.

3 Results

3.1 Determination of the biomass potential for aquatic plants in standing waters

3.1.1 Area yields for aquatic plant biomass

The average area yield for biomass of *Elodea* from the lakes “Cospudener See” and “Seelhausener See”, which was harvested to a depth of 6 m, was 0.42 ± 0.11 kg DM/m². For biomass of *Myriophyllum* taken from “Cospudener See” and “Heider Bergsee” to a depth of 4 m, the average yield was 0.59 ± 0.11 kg DM/m² (Table 1). In the investigated lakes, the aquatic plants were found down to a maximum depth of 6.5 m. The stocks were lighter, the deeper the plants grew. The plants reached a height of between 1.2 and 3 m in the examined waters. The average fresh mass was 7.9 kg per square meter at a depth of 2 m and only 7.4 kg at a depth of 4 m. The plants of the genera *Elodea* and *Myriophyllum* often occurred in the same waters. In “Cospudener See” in Leipzig, two thirds of the shore area (especially the west, south, and south-east shores) had pronounced aquatic plant populations at depths of between 1 and 6 m, especially of the genera *Elodea* and *Myriophyllum*.

For further calculations of the potential of aquatic plant biomass (Table 2), a mixed water plant population with 50% *Elodea* and 50% *Myriophyllum* was used as the basis with the following data: 7.1 kg/m² area yield fresh mass, 0.5 kg/m² area yield DM, 0.4 kg/m² area yield oDM, 347 Nm³/Mg_{oDM} biogas yield, and 197 Nm³/Mg_{oDM} methane yield [15]. The data were calculated from the species-specific analyses and the proportion of the mixed population. The total and usable potential of aquatic biomass was calculated on the basis of the surface waters of 695 lakes in Mecklenburg-Vorpommern. Four scenarios with different degrees of growth with aquatic plants are considered (Table 2).

Using the data from Table 2, an attempt was made to estimate the potentially usable aquatic plant biomass from all standing waters in Germany. For this, it was assumed that the percentage of the water surface determined for Mecklenburg-Vorpommern for areas with water depths of 0–2 and 0–5 m relative to the total surface of the water is sufficiently accurate for an estimate of the biomass potential of water plants for the whole of Germany. From our own experience in field research, water plant coverage of 25% of the shore area—where sunlight penetrates all the way to the sediment and allows aquatic plants to grow—is regarded as a realistic scenario.

This estimation results in the following potentials for aquatic plant biomass from all standing waters in Germany with a size of greater than 4 ha: usable potential of 1 995 483 Mg area yield wet weight, 140 527 Mg area yield DM, 112 422 Mg area yield oDM, 39 010 434 Nm³ of biogas, and 22 147 134 Nm³ of methane.

3.2 Biomass quality

The DM content of aquatic plant biomass from the 35 samples of the water plant harvest in autumn 2015 and summer 2016

Table 1. Aquatic biomass in three lakes: quantitative determination of biomass growth on one square meter (with three repetitions) at different depths, dry matter (DM) and organic matter (oDM) of the aquatic plant samples

Lakes		Depth	Fresh mass [kg]	DM [% FM]	oDM [% DM]
Cospudener See	<i>Elodea nuttallii</i>	2 m	8.53 ± 2.02	6.08 ± 0.72	76.51 ± 3.34
		4 m	6.80 ± 1.04	5.39 ± 0.15	73.06 ± 2.42
		6 m	4.97 ± 0.75	6.02 ± 0.16	58.53 ± 5.93
Seelhausener See	<i>M. heterophyllum</i>	2 m	7.40 ^{a)}	9.64 ^{a)}	71.95 ^{a)}
		4 m	7.00 ± 2.07	7.10 ± 2.12	76.71 ± 3.29
Heider Bergsee	<i>Elodea nuttallii</i>	2 m	7.67 ± 0.93	7.08 ^{a)}	68.35 ± 0.56
		4 m	8.53 ± 0.65	6.00 ^{a)}	80.69 ± 1.49

^{a)} Single determination

Table 2. Usable potential of aquatic biomass from 695 lakes in Mecklenburg-Vorpommern (Germany), considered in four scenarios with varying extents of water plants

General data on lakes (n = 695)				
Total water surface [m ²]	751 903 805			
	Usable potential ^{a)}			
Water surface at 0–2 m water depth, total [m ²]	217 644 711			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Surface at 0–2 m water depth, overgrown [%]	100	75	50	25
Surface at 0–2 m water depth, overgrown [m ²]	217 644 711	163 233 533	108 822 356	54 411 178
Yield total FM [Mg]	1 545 277	1 158 958	772 639	386 319
Yield total DM [Mg]	108 822	81 617	54 411	27 206
Yield total oDM [Mg]	87 058	65 293	43 529	21 764
Biogas [Nm ³]	34 823 154	32 646 707	17 411 577	8 705 788
Methane [Nm ³]	19 849 198	14 886 898	9 924 599	4 962 299

^{a)} Settlement area of aquatic plants that can be harvested with commercially available harvest boats.

varied between 5 and 22%. The organic content averaged 83.4% TS and the C/N varied from 10.8 to 31.8. The sediment content of most samples was less than 1% of the DM of the total material.

3.3 Silage of aquatic plant biomass

The results of the storage tests show that waterweeds can be stored by ensiling. The pH values were between 4.9 and 6.5 and the volatile fatty acid content in the form of lactic acid ranged from 0.0 to 1.9% TS. Even the 6.5 pH silages were preserved for over 12 months. However, the storability of plant material alone is challenging, as the water content is about 95%. In contrast to pure *Elodea* silage, mixed silage of waterweeds and cereal straw was suitable for storage in clamp silos. The methane potential of pure *Elodea* silage with 6.7% total solid content was 219 mL/g_{VS}. The mixed silages achieved methane potentials of between 166 and 228 mL/g_{VS}, which is equivalent to 52 and 72% of maize silage. The highest methane potential of 228 mL/g_{VS} was measured with mixed silage from waterweeds and ground straw with 30% total solid content. Considering the methane potential of 206 mL/g_{VS} and the effort required for material pretreatment, the most promising silage variant for practical applications was mixed silage from waterweeds and chopped straw with 30% total solid content.

3.4 Social aspects

The analysis of data from the questionnaire, the media analysis and the qualitative interviews revealed four stakeholder groups: nature conservation, water construction and maintenance, industry and commerce, and finally tourism and recreation. The analysis also demonstrates that the arguments of the stakeholder groups are diverse, although a clear division between nature conservation and all other stakeholder groups can be detected. Stakeholders from the nature conservation group state arguments both for and against de-weeding, and thus have a differentiated view. On the other hand, all other stakeholder groups view de-weeding as positive, with their perception of the issue concentrating on only a few aspects. It also became clear that stakeholders often have very limited knowledge of the positions of other stakeholders. The results on social aspects have been published in detail in Ref.16.

4 Discussion

4.1 Biomass potential for aquatic plants from standing waters in Germany

A sample calculation should help to clarify the relevance of the above-mentioned potential of aquatic plant biomass.

The average yield for maize, which is the plant most commonly used for biogas production in Germany, is 45 Mg/ha (http://www.lfl.bayern.de/iba/energie/049711/?sel_list=12%2C&b&anker0=substratanker#substratanker [Accessed on 12 February 2018]). Silage losses of 10% should also be considered in this estimation. The methane yield of maize is 96.7 Nm³ CH₄ per Mg_{FM}. It follows that 3917 Nm³ CH₄ can be produced from one average hectare of maize in a biogas plant. The methane potential of 22 147 134 Nm³ CH₄, which could potentially be obtained from aquatic plant biomass per year in Germany, thus corresponds to a methane yield of 5654 ha of maize.

4.2 Quality of aquatic plant biomass

As regards quality from the point of view of a biogas plant operator, aquatic biomass is comparable to vegetable waste in terms of biogas yield and C/N. The sediment content is also comparable to other conventional substrates. As a result, aquatic biomass should not pose any problems in terms of fermentation biology and technology. With regard to heavy metals, special attention should be paid to the elements zinc and nickel, since these are very mobile and can be absorbed by aquatic plants from sediment [17]. High zinc and nickel contents in the input material can lead to a sufficient amount of these essential trace elements in the biogas plant, depending on the substrate mixture and the contents of the other substrates, or can lead to an overload in the digestate, changing it from a fertilizer to a waste.

4.3 Silage of aquatic plant biomass

Single storage of aquatic plant material will require silos for liquid ensiling in practice due to its high water content, whereas mixed silages from *Elodea* and cereal straw with a total solid content of between 30 and 45% show suitable substrate characteristics for storage in common agricultural clamp silos. Although experiments have only been carried out on a laboratory scale, the mixture of waterweeds with straw to a DM of ~30% can be recommended for practical applications. Due to capacity restrictions, the experiments were only carried out with wheat straw. In principle, mixtures of waterweeds with different, drier lignocellulosic substrates are possible. Typical harvesting periods for aquatic weeds are summer time for recreational bodies of water and autumn for rivers (protection of water structures against aggradations). For this reason, different mass flow combinations (e.g. a combination with maize straw in autumn, with cereal or rape straw or with landscape material in summer) and efficient process chains need to be investigated.

4.4 Social aspects

Overall, the level of conflict between stakeholders does not appear to be very high, given the fact that many bodies of water in Germany undergo de-weeding. However, the identification of

four stakeholder groups and their positions helps institutions responsible for the maintenance of bodies of water to anticipate conflicts and deal with them constructively.

As mentioned in the introduction, cost is a key issue alongside the four aspects discussed in this paper. As of now, there is no established value chain for using aquatic biomass in biogas plants. Such a value chain would have to include cutting, collecting, transport, pretreatment, ensiling, and fermentation. The first steps in this value chain in particular are far from being cost optimized. For a plant operator, the key question is whether aquatic biomass is competitive with conventional material, such as maize silage over the entire value chain. In calculating cost, two cases need to be considered: firstly, a case where the biomass would have been harvested anyway to ensure continued use of the body of water, e.g. for recreational purposes. In this case, cutting, collecting, and transport would not be included in the cost of using aquatic biomass when comparing it with maize. If, as a second case, the biomass is only harvested for the purpose of using it as biogas feedstock, the first three steps would then have to be included. A preliminary analysis of the value chain clearly shows the main cost drivers: firstly, the disposal cost for the aquatic biomass, which can exceed 100 euros per ton; secondly, the cost of straw if the water plants are ensiled with straw; and thirdly, the use of aquatic biomass due to its low DM content results in a low biogas potential, which drives up the amount of digestate, and as a result digestate disposal costs also become a major factor.

4.5 Lessons learned

The estimation of the biomass potential has shown that aquatic biomass could replace around 6000 ha of maize, depending on the assumptions made. Put into perspective with the total acreage used for cultivating maize for biogas plants in Germany of nearly 1 000 000 ha or the total acreage of energy crops in Germany of around 1 450 000 ha, it is evident that aquatic biomass—even in an optimistic scenario—can only be a niche approach on a national level. For single biogas plants or specific regions with many lakes, however, aquatic biomass could be an attractive option. And even if it replaces only a small fraction of conventional feedstocks, it could certainly form one element in an effort to achieve environmentally friendly feedstock diversification, which is important for the further development of the biogas industry. The analysis also shows that the material is manageable for biogas plants from the perspective of ensiling and fermentation biology. So, what is needed for establishing aquatic biomass as a future feedstock in biogas plants? Technology along the value chain needs to undergo significant technical improvements—especially cutting and collecting—and robust cost estimates need to be established. These are tasks for researchers and industry for the coming years. The unclear legal status of aquatic biomass is another challenge for industry that needs to be tackled by political decision-makers and authorities. Finally, when using aquatic biomass, actors need to keep in mind the diverse and sometimes conflicting interests of stakeholders in bodies of water in order to garner support for de-weeding and using aquatic biomass in biogas plants.

Practical application

This research has practical applicability at several levels. In the area of municipal government and administration, the potential analysis shows a possibility for both reducing disposal costs and nutrient loads in bodies of water and for renewable energy generation with no competing uses. These advantages should lead to adapted regulations that enable the digestion of aquatic macrophytes (currently only plant growth on shore is defined as landscape material in Germany, so undefined growth in bodies of water is usually seen as waste). For biogas plant operators, the potential analysis clearly reveals the potential of this competition-free substrate. The ensiling and digestion results can be directly used by plant operators and plant constructors for the planning and operation of biogas plants with aquatic macrophytes based on a seasonal or year-around strategy. The relatively high methane yields either alone or in mixtures with straw allow for effective plant operation.

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