Journal of Energy and Environmental Sustainability, 11 & 12 (2022) 1-5

An official publication of the International Society for Energy, Environment and Sustainability (ISEES)

Journal of Energy and Environmental Sustainability

Journal homepage : www.jees.in

Challenges vis-a-vis Opportunities of Aquatic Biomass Weeds

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A R T I C L E I N F O

Received : 18 September 2020
Revised : 05 November 2020
Accepted : 05 November 2020

Keywords:
aquatic biomass,
waste to energy, water hyacinth,
resource management, bioenergy

A B S T R A C T

The global energy system is in needs of major transformation for sustainable development, climate change mitigation and adaptation. Dependence on depleting fossil fuel reserves calls for alternate energy sources which are abundant yet untapped. The potential of aquatic biomass (AB) as an energy source is a highly topical subject; however, there is little discussion on its conversion, evident from limited commercial installations.Inadequate mapping, weak supply network, lack of awareness and policy-related challenges are some of the roadblocks or effective utilization of AB. This article briefly reviews the potential of AB, possible areas of applications and provides afflatus to refocus the eradication measures towards sustainable resource utilization by offering a solution for converting waste into valuable resources via integrated resource management.This review can aid waste-to-energy practitioners, regulatory bodies, research institutes and relevant stakeholders for developing strategies in line with decarbonization targets.

1. Introduction

The vectors of the energy extraction are vulnerable to climate change due to continuous and potentially irreversible changes in climate parameters, posing a challenge to accomplish national/international decarbonization goals [Cronin et al. 2018]. Renewable energy supply is susceptible to the impacts of climate change, solar (PV and concentrated), wind (offshore and onshore) and hydropower may get uncertainly affected [Gernaat et al. 2021]. Also, achieving 100% renewable energy electric power is challenging due to two significant reasons, (a) seasonal imbalance between supply and demand causing nonlinear cost and (b) new flexible design requirements of power systems [Denholm et al. 2021]. Additionally, the pipeline of proposed coal power plants has declined by 76% globally since 2015, effectively putting new plants out of sight [Littlecott et al. 2021]. In such challenging times where abandoning coal power projects and the influence of climate change on renewable energy are simultaneously observed, the solution should direct the roadmap for future sustainable energy harvesting methods. Therefore, the global interest should target the utilization of untapped natural resources for energy exploitation. These underestimated natural energy sources must be in tune with the current energy demand-supply trends to support/substitute the conventional or modern energy sources. Moreover, future energy security can be assured with indigenous sources considering maximum depletion of conventional fuel resource.

Most of the initiatives for cleaner energy deployment are inclined towards solar or wind projects across the globe [Carley and Konisky 2020; Hairat and Ghosh 2017]. Due to vagaries in nature and storge-related issues, sole dependence on solar and wind energy sources is deceptive [Sinsel et al. 2020]. A shift from fossil fuel to biofuel (ethanol) is gaining traction; however, high dependence on the crop for biofuel production may spark food vs fuel row [Subramaniam et al. 2019].

Considering the above challenges, this paper explores the possibility of using aquatic biomass (AB), the extent of which is not fully realized in the waste-to-energy scenario. AB is associated with a high growth rate, making it a potential raw material for future energy needs. The paper also attempts to address the eradication and cultivation discussions of AB and concludes with the necessity of sustainable harvesting and value addition methods.

2. Aquatic biomass weeds

Noxious free-floating AB weeds remain an untapped species with potential for effective utilization.These aquatic weeds have a certain advantage over terrestrial biomass interms of lower lignin content, high productivity rate and the fact that they don't require arable land [Nawaj Alam et al. 2021]. AB weeds are proliferated around the globe in every temperature zone. Region-wise compilation of all beneficial aquatic weeds is presented by Nawaj Alam et al. [2021], water hyacinth (WH) being the most prominent and found worldwide area including India, America,

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Zimbabwe, Egypt, Malaysia, Indonesia etc. [Thamaga and Dube 2018]. The application of AB for energy & industrial feedstock can be a suitable option to counter invasive growth issues on the sustainable ground.

Fuel analysis and composition of commonly found AB is presented in Table 1. Their calorific value is competitive to coal and refused fuels. Additionally, high energy value, nutritional content, source of other chemicals (protein, fibre, lipids etc.) make AB a valuable bioresource [Gusain et al. 2018]. However, the high moisture content of newly cultivated AB is the primary concern, significant energy in required for de-watering, there by increasing overall cost of the process. Also, the moisture removal methods/techniques sometimes challenge the 'green nature' of fuel products (pellets/briquettes) when the energy for dewatering is derived from fossil fuels. The use of solar dryers can offset such intense energy requirements. More research is required on available solar insolation, day length and drying time. Baso et al. [2021] concluded that increasing ambient CO_2 concentration primarily driven by climate change would make the control of weeds more challenging. The challenges and demerits of AB proliferation are summarised in Table 2.

The socio-economic damage caused due to aquatic weeds can be averted by using them as resources for fuel, chemical and material production. Zehnsdorf et al. [2018] estimated the huge potential of AB, which could replace 6000 ha of maize. The worldwide potential of terrestrial biomass is approximated as 40-1100 EJ; contrarily, the potential of AB stands 6235 EJ [Florentinus et al. 2008]. These are old and conservative estimates made with non-reliable traditional surveys and obsolete mapping technology with poor detecting range and ability [Thamaga and Dube 2018]; the original figure may be much higher. Therefore, the farming of AB for better yield requires identifying basic parameters influencing growth and cultivation. The parameters for growth and cultivation are outlined in Table 2.

The amount of solar irradiation, depth up to which these radiations are available, temperature and nutrient availability triggers the growth of AB. Similarly, local weather conditions, free-floating or anchorage nature and area of proliferation are the prime factors for the cultivation of AB. The above discussion (from Table 2 & 3) sets the base for nurturing AB or using control measures (discussed further).

3. Estimation of aquatic biomass

Although the challenges of AB are well addressed, its distribution in oceans, rivers, water streams, ponds are not fully surveyed. The assessment of the available quantity of AB is limited as most of the weeds are identified in lakes, rivers, and basins near human settlements [Gusain and Suthar 2017]. However, little is known about their quantity in remote and inaccessible areas away from human habitats [Yadav et al. 2017]. Moreover, access to AB depends on area and local water body conditions (Table 3), adding to logistical issues, difficult convenience, and involved cost pose a challenge in mapping the entire AB.

The utilization of AB for energy purposes requires accurate quantity assessment across the spatio-temporal scale. Advanced tools and materials can be instrumental in measuring the quantity and species of AB grown such as identification in crops with multispectral imagery [de Castro et al. 2012], multisensory Landsat images [Nyamekye et al. 2021], machine learning [Akbari et al. 2021] and hyperspectral remote sensing [Hestir et al. 2008] assisted by unmanned aerial vehicles (UAVs) such as drones [Göktoçan et al. 2010; Vahtmäe et al. 2021]. Such tools can aid in designing future abatement strategies of unwanted species and valuable resource assessment [Dersseh et al. 2019].

4. Applications of aquatic biomass

AB can be classified based on their nature of proliferation, i.e.,free-floating, submerged and emergent; however, the final application of the AB remains largely the same [Kaur et al. 2019]. Figure 1. summarises the types and application areas of AB reported in literature. The applications

Table 1. Fuel analysis and composition of common aquatic weeds [Kaur et al. 2019]

Aquatic weed	C (%)	H (%)	N (%)	S (%)	Volatile matter (%)	Calorific value (MJ/kg)	Cellulose (%)	Lignin (%)
Eichhornia crassipes	40.1	5.3	1	-	61.2	14.4	24.5	8.6
Ulvalactuca	23.9	4.6	1.5	-	46.4	10.2	10.8	1.4
Ledermannie-llaschlechteri	36.2	4.4	2.1	-	62.8	14.3	21.9	1.4
Azolla microphylla	52.6	7.3	2.1	-	44.3	12.1	27.4	17.3

Table 2. Challenges of expansive growth of aquatic weeds

Sr. No.	Challenges	Description	References
1	Restrain growth of other species	Agro-species having food value gets suppressed due to the invasive nature of AB weeds leading to restricted yield.	Nawaj Alam et al. (2021)
2	Overgrowth	Excessive growth promotes sediment deposition and siltation, leading to diminishing water body depth.	Bote et al. (2020)
3	Occupy the living space of fauna	Limits the space for fauna movement causing excessive survival competition.	Nawaj Alam et al. (2021)
4	Reduces the sunlight penetration	The mats of weeds reduce light penetration affecting the nutrient cycle.	Charudattan (2001)
5	Affects other social and economic activities	Restrict the movements for aquaculture, agriculture, fishing and block the irrigation pathways.	Güereña et al. (2015)
6	Perennial nature	Sheets of aquatic weeds spread over a large area and existing for a longer duration may reoccur after opting for control measures.	Malik (2007)
7	Breeding ground for mosquitoes and other pests	Makes water stagnant, helping in the nesting and growth of snakes, mosquitoes and other pests.	Nawaj Alam et al. (2021)
8	Reduces water level	Evapotranspiration rates of aquatic weed infested water bodies are more than twice than that of the free water surface under equivalent conditions	Ali and El-Din Khedr (2018)
9	Blocking water streams	The proliferation of AB causes a restriction to the flowing water resulting in waste diffusion near shores.	Güereña et al. (2015)
10	GHG emissions	The mass decomposition of AB consumes dissolved oxygen from the water and emit methane and other greenhouse gases.	Ochumba & Kibaara (1989)

Table. 3 Parameters defining the growth of AB [adapted from Florentinus et al. 2008]

Sr No.	Parameters		Description
1.	Growth	Irradiation	Level of photosynthesis (and therefore, growth)
		Temperature	Optimum temperature between 15-30 °C
		Nutrients	Phosphate, nitrogen, iron, CO_2
		Limpidity	Zone of irradiation, i.e., depth to which sunlight can penetrate
2.	Cultivation	Sea/local water body conditions	General weather condition, water current, water depth
		Substrate	Place of anchorage
		Logistics	Accessibility for AB cultivation
		Area	Coastal, lakes, ponds, open ocean

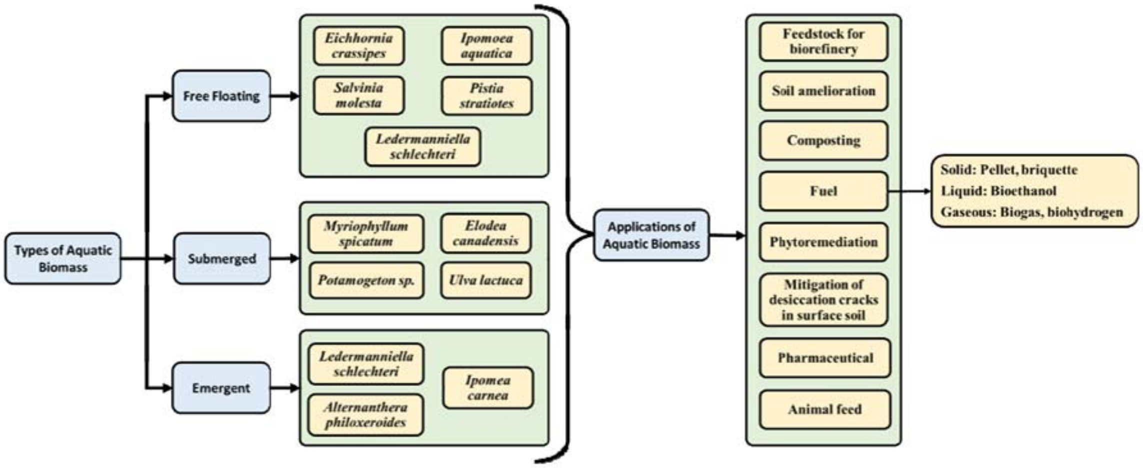

Figure 1. Types and applications of aquatic biomass

of AB include energy harvesting, water treatment, food (feedstock), pharmaceutical industries like sectors and can be supplemented in the recapitulation of natural resources. Researchers have tried and tested the suitability of AB in fuel production, remediation of water bodies, nutrient extraction (pharma industries), crop fertilizer and many more; the range of outcomes shows a possibility of successful field implementation and associated challenges.

Removal of heavy metals from conventional treatment technologies is costly, inefficient, time-consuming and recognized for causing environmental damage. WH, water lettuce, duckweed, and other AB accumulates heavy metals and remediate water bodies [Ali et al. 2020]. AB can resolve such resource-intensive issues and alternatively be used as feedstock for biochar conversion [Roberts et al. 2015]. AB also helps in cycling excess nutrients in the waterways [Winton et al. 2020].

The consequences of fuel derived from lignocellulosic biomass include monoculture, challenge of food security, deforestation and ecological impacts [Ullah et al. 2015]. Even with the recent advancement, the use of lignocellulosic biomass harvested only for its fuel value can still cause water and land pollution [Dominguez-Faus et al. 2009]. The food vs fuel debate does not apply to AB because of its (i) noxious nature (not suitable for human consumption), (ii) rapid growth, and (iii) widespread availability.

AB has already marked its presence as a future feedstock for biorefinery; currently, all forms of fuels, i.e., solid, liquid and gaseous, can be derived in a similar process chain as terrestrial lignocellulosic biomass [Bharathiraja et al. 2015]. Biogas production from AB (WH) with anaerobic digestion was explored by Bote et al. [2020]; the digestion residue was used for making briquettes that can be further mobilized as a substitute for wood in cooking/heating. Mathew et al. [2015] confirmed a better biogas production yield of 552 L kg^{-1} volatile solid from WH than conventional methods. Furthermore, biogas generation from AB is economically feasible rather than its disposal [Herbes et al. 2018] and can be further used for electricity generation [Njogu et al. 2015]. The possibility of biohydrogen production from AB through dark fermentation was investigated by Mthethwa et al. [2018], obtained yield ranged from 2.46 ± 0.14 mol-H_2/mol-glucose at 22.8 \$/kg-H_2 production cost. The yield bioethanol obtained from AB is also promising; Kaur et al. [2019] reported 0.167–0.231 g/g biomass comparable to conventional bioethanol securing processes which can be used as jet fuel [Baliban et al. 2013]. Similarly, Sunil et al. [2015] reported 113.33 g/mL of bioethanol yield from AB. Additionally, AB finds application in making solid fuels like briquettes and pellets, can be employed as thermal and lighting energy sources [Munjeri et al. 2016; Onyango et al. 2020]. Heating values of AB (WH) are consistent with coal [Muhammad et al. 2016] and can be blended with coal as support for waste to energy initiative [Hanazawa et al. 2008; Yuan et al. 2011].

A unique application of AB can be taken from Mei et al. [2021] study in which biochar derived from WH was used to reduce the evaporation rate of densely packed soil and increase water holding capacity. Furthermore, the AB extraction for making antioxidant, anti-obesity drugs is gaining popularity [Sarmiento Padilla et al. 2021]. Interestingly, AB has nutritional qualities; a study confirmed protein content of 11.0-32.2 % by weight with protein to energy ratio of 30.7 gm/kcal and presence of vitamin E and C [Kalita et al. 2007]. AB can be reinforced as nutraceuticals in fish feeds [Mukherjee et al. 2010].

Currently, waste-to-energy applications (including biofuels production) from AB are not economically viable, as cultivation, separation, and extraction are costly; however, technological advancement may enable commercialization [Bharathiraja et al. 2015]. Also, the limited field applications, developing technology and unsustainable AB harvesting pose a challenge for its multi-dimensional use.

5. Aquatic biomass weeds: eradication orcultivation?

The opinionovercultivation vs eradication of AB weeds is dispersed. It is not clearly cited in the literature about the choice related to the control of AB through its cultivation or adoption of control measures. As discussed earlier, the nuisance created by AB in the natural ecosystem and its broad spectrum of applications as fuel and materials makes the controlled and sustainable cultivation look promising rather than opting for growth-limiting techniques. The ecological catastrophe originated due to AB can be effectively converted into monetary, social, economic and environmental benefits. Comparison between **Table 1** and**Table 2** presents a suitable decision marking point for AB in a particular locality.

The majority of the conventional control measures are non-automated, manual and time-consuming [Abbas et al. 2018].Costs of control measures (mechanical, biological and chemical)sometimes exceed the benefits [Van Oijstaeijen et al. 2020]. Contrarily, an economic analysis revealed that opting for control measures benefits the revenue generated from the business related to boating, waterfowl hunters and anglers (Wainger et al. 2018]. However, this analysis was limited to a typical set of applications and locations. Some weed species may react inversely to the herbicide used during the de-weeding. Factors including lack of proven field applications, funding and institutional challenges directly impact the effectiveness of weed control measures [Van Wyk and Van Wilgen 2002]. Therefore, the control measures should also prefer identifying and classifying AB species with smart, automated tools for applying correct herbicide [Pereira et al., 2012]. Failure to consider these can lead to reoccurrences of AB and loss of efforts and resources.

The nascent energy extraction techniques are the driving force behind the preference of control measures over cultivation.The harvesting/extraction technology is limited and accompanied by higher operating costs [Güereña et al. 2015]. Also, the AB conversion should first consider the species, growth, ecological function, morphological characteristics [Cao et al. 2021].Other considerations for effective cultivation include the proximity of the cultivation plant from the infested site as the AB can start to decompose after its removal from the water body (this can be made up via a mobile cultivation unit), and the ability to recycle the water in the AB back into the water body, since AB is associated with very high moisture content.

To eradicate AB invasion, the integrated approach is required to ensure minimum chances of reoccurrence. On the other hand, it is also a prerequisite to comprehensively evaluate the effect of eradication or cultivation of the health of aquatic ecology to prevent future risk [Su et al. 2018]. Newer technologies with improved fuel production facilities are required to finalize the choice between AB extraction for energy purposes and eradication.

In conclusion, the eradication vs cultivation of AB should be based on the opportunity in the valuable conversion. Fuel value, the possibility of material/chemical extraction with minimum environmental impacts andthe ability for employment generation are critical parameters for cultivation. On the other hand, if the effective conversion in a locality is way more challenging and costly, then the eradication practices of AB with advanced tools should be undertaken.

6. Conclusion

The abundant availability andfastgrowth,together with the basket of applications, make AB a suitable resource option. Moreover, being an aquatic weed, the cultivation does not affect/displace the valuable farming land.

The following points needs the attention of the scientific/technical community, waste to energy practitioners, responsible government agencies.

- The quantification of AB is a challenge for waste using industry that needs to be tackled by survey/field/aerial monitoring.
- The widespread distribution and variety of AB (other than WH) across regions show a large underestimate of utilization capacity.
- R&D on harvesting methods, efficiency, drying approaches along with efficient pre-treatment and conversion technologies should be streamlined.
- The plans of diverse utilization of AB should acknowledge environmental burden through comprehensive life cycle impacts, techno-economic feasibility studies and cost-benefit analysis.

Finally, the preference to integrated self-sustaining waste management strategies of AB by incentivizing the management efforts through novel technologies needs attention.

Acknowledgments

The authors thankfully acknowledge the Council of Scientific and Industrial Research (CSIR), India and the Director, National Environmental Engineering Research Institute (NEERI), for supporting the research.The manuscript is checked for plagiarism using licensed iThenticate software through CSIR-NEERI Knowledge Resource Centre wide KRC No. CSIR-NEERI/KRC/2021/OCT/ERMD-DZC/1.

Declaration of competing interest

The authors declare no competing financialinterests or personal relationships that could have influencedthe work reported in this paper.

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