Bioenerg. Res. (2015) 8:1589–1597
DOI 10.1007/s12155-015-9639-5

Utility of Duckweeds as Source of Biomass Energy: a Review

Rashmi Verma[1] · **Surindra Suthar**[1]

Abstract The quest for alternative sources of energy has evoked the interest in exploring potentials of living biological wastes as new energy materials. Duckweeds are produced abundantly as weeds in freshwater surface bodies and can be a source of biomass for bioenergy productions. There are approximately 40 species of this group worldwide belonging to five genera (*Spirodela*, *Lemna*, *Wolfiella*, *Wolffia* and *Landoltia*). The structural peculiarities (small plant size, limited life cycle, high duplication rate, etc.) and chemical characteristics (dry weight basis): 17.6–35 % (carbohydrate), 21–38 % (starch), 16–41.7 % (crude protein), 8.8–15.6 % (crude fibre) and 4.5–9 % (lipid) make duckweed as possible feedstock for biomass-based energy operations. The high contents of valuable fatty acids (palmitic acid and linoleic acid) and starch (3–75 %) in duckweed biomass suggest its utility in biorefinery. Recent lab-scale studies have shown remarkable results in terms of energy yield during the processes like anaerobic digestion, incineration, pyrolysis, gasification, oxidation, etc. Another good quality of duckweeds is its hyperaccumulative properties for a variety of water pollutants. Therefore, this group of weeds has been recommended widely for designing on-site phytoremediation system for community wastewater treatment. Thus, duckweed technology can be adopted as coupled technology to harness two environmental approaches, i.e. wastewater treatment and energy biomass production for sustainable development of the human society.

Keywords Bioenergy · Biomass energy · Wastewater treatment · Starch · Palmitic acid

Introduction

The energy is one of the important factors that drive development process of any country. It provides the stimulus and momentum to socioeconomic development of any developing society [1]. Therefore, the secure and accessible supply of energy is an inevitable need of modern society. The energy consumption pattern grows linearly with economic growth and industrial development [2]. The major proportion of energy demands is fulfilled by non-renewable sources such as natural gas, coal and petroleum derivatives [3]. Globally, the future energy demands will recklessly rise with population growth and increasing living standard of the society [4]. The excessive consumption of fossil fuel tends to diminish the availability of resource for future generations [5]. The fossil fuel-based energy is finite and produces by-products, such as greenhouse gases, that are detrimental to the environment [5–7]. The continued use of fossil fuels will set to face multiple challenges related to depletion of fossil fuel reserves, global warming and other environmental concerns, political and military conflicts and ultimately significant fuel price rise [7]. The necessity of proper management of existing energy resources and exploration of new energy resources is essentially needed to address. The transformation of energy economy based on vast, expensive supplies of coal, oil and natural gas to much cleaner and easily accessible wind, solar and biomass energy will help to mainstream energy demand [2]. Renewable energy is advocated to be the possible solution of growing energy challenges as they are abundant, inexhaustible and environmentally friendly [8]. The exploration of non-carbon energy sources such as solar, nuclear, biomass, wave, tidal and

✉ Surindra Suthar
sutharss_soilbiology@yahoo.co.in

[1] School of Environment and Natural Resources, Doon University, Dehradun, Uttarakhand 248001, India

geothermal may provide sustainable solution for long-term availability of energy resources [4, 5, 9]. Biomass (including organic matter derived from living organisms) forms the most utilized sources of renewable energy and accounted for 10.2 % of global primary energy supply [1, 10, 11]. The biomass-based bioenergy production has several issues like availability of raw material, productive conversion processes, water and energy requirement, etc. [12]. In this process, the efforts are being made in searching viable plant resources for designing a cost-supportive biorefinery system [13]. On the other hand, the production of bioenergy (biofuels, biogas and bioelectricity) outsourced from renewable biomass feedstock is advocated as an energy alternative with low-emission potentials in terms of carbon budget [14]. The feedstock utilized for this purpose mainly includes post-consumer organic residues and by-products available from community wastes, agriculture and forest industries: crop residues, forest and wood process residues, animal excreta, sewage sludge, municipal solid wastes, food processing wastes, purpose grown energy crops (*Miscanthus*, *Jatropha*, *Salix*, *Panicum*, *Eucalyptus*) etc. [10, 15]. Worldwide, there are multitudes of plant species that can be used for several energy generation purposes like oil, heat, bioethanol, power production, etc. In this series, biofuels form the largest category of bioenergy derived from biomass. The principal fuels that can be manufactured includes ethanol, methanol, biodiesel and hydrogen; although, other categories of fuels such as biobutanol and dimethyl ether can also be produced from plant biomass [16, 17].

The thermal characterization of plant biomass is an important aspect of bioenergy production process. The proximate (moisture, ash, volatile, total carbon content) and ultimate (elemental composition such as C, N, H, S and O content) analysis of energy biomass play an important role in determining the energy potential of a plant feedstock [15]. The collaborative interaction between moisture contents and bulk density prescribed the heating value of the biomass and also decide the appropriateness of conversion process [1]. The total solids and volatile solid content of any liquid/solid material can have direct impact on the bioenergy production efficiency. The ideal biomass destined to be used for bioenergy production should have efficient solar energy conversion resulting in high yields, needs low agrochemical inputs, has a low water requirement and has low moisture levels at the time of harvest [14, 18, 19]. Conventionally used plant species may not address the issue of sustainability; therefore, the utility of plant species that demarks the direct interference with food security is critically needed.

Aquatic biomass is ubiquitous and grows in different environmental and climatic conditions [20, 21]. Water hyacinth (*Eichhornia crassipes*), water lettuce (*Pistia stratiotes*), frog's bit (*Limnobium spongia*), water fern (*Salvinia minima*), mosquito fern (*Azolla caroliniana*), water lily (*Nymphaea mexicana*), American lotus (*Nelumbo lutea*), water spinach (*Ipomoea aquatica*), duckweed (*Lemna* sp.), watercress (*Rorippa nasturtium-aquaticum*), etc. are few prominent species that offers flexibility in terms of water utility and environmental requirements for optimal growth [22]. However, the utility of local aquatic plant species strains other than exogenous species strain will helps to maximize the growth rate and ultimately bioenergy yield [23]. The adaptability of different aquatic plants to grow on a variety of wastewaters also diminishes the utility of freshwater resources for such purposes [24, 25]. Apart from having great energy values, the aquatic plants have been utilized effectively for on-site wastewater treatment approaches [25–27].

Thus, this can lead to develop a coupled system for wastewater treatment and energy biomass harvesting. The use of aquatic plants especially weed species as bioenergy feedstock is often a remarkable alternative as it offers plant biomass harvesting, utility of wastewater resources, high energy return on investment, potentially greater economically efficiency, little or no conflict with food resources and much lower greenhouse gases (GHGs) emissions and other environmental effects [16]. This review summarizes the potential and feasibility of duckweed as bioenergy feedstock for sustainable urban habitat development.

Duckweed as a Resource for Bioenergy

Ecology and Morphology

The aquatic vascular monocotyledons angiosperms duckweed belongs to the family Lemanceae [21]. It is represented by 5 genera: *Spirodela* Schleid., *Landoltia* Les & D. J. Crawford, *Lemna* L., *Wolffiella* (Hegelm.) Hegel and *Wolffia* Horkel ex Schleid [28–30]. According to the reported literature, there are approximately 38 species of duckweeds distributed worldwide in freshwater ecosystems [31]. This plant inhabits in a wide range of aquatic ecosystems from tropical to temperate zones, and from freshwater to brackish estuaries, except arctic and antarctic zones. Duckweed occurs abundantly in still or slightly moving water, but flourishing growth is reported to occur in stagnant ponds, brackish water or ditches rich in organic matter, or near sewer outlets [31].

All five genus of Lemnaceae offer physiological plasticity and peculiar morphological and physiological features that account for their classification and differentiation [29]. Various morphological features (frond size, root pattern, flower pattern, etc.) are used, in general, to differentiate between different duckweed species [30]. In case of *Wolffia*, roots are absent, fronds are without nerves, the daughter fronds and flowers are originated from cavity or pouch present at the base of frond, scales are usually absent in flowers and seeds are smooth [29]. Whereas, in *Lemna*, roots are generally present and varies from 2–21 per frond, frond are with nerves, the daughter fronds originate from two lateral pouch present at frond base, flowers are surrounded with scales and seed are longitudinally ribbed [30]. Generally, plant body consists of fronds and with or without roots. Fronds are poorly differentiated and flattened, small leaf-like or spherical in shape [28, 32]. The number varies from one, two or to many and are cohering together at base. In size, it is 0.05–1.5 cm long (without stalk) and 0.03–1 cm wide, thin or thick. Roots are bottom lined and without root hairs. The major cellular constituents are chlorenchymatous type with large intercellular spaces. This helps to provide buoyancy and supports free floating nature [29]. To withstand unfavourable conditions and dormancy stage of lifecycle, turions are formed [29]. These are compact frond reduced in size and structure and filled with starch grains. Flowers are rarely present in plant. If present, 1–2 per frond in number, mostly perfect with no sepals and petals. Stamens are 1 or 2 and ovary 1, bottle-shaped characterized with short style and funnel-shaped stigma. Fruits are generally seeded (1–5) with dry pericarp. The chromosome number reported by counting somatic (root tip) chromosomes are 2n equal to 40 in *Spirodela polyrrhiza* and *L. minor*, 44 in *L. triszlca*, 64 in *L. gibba* [33]. The proliferation primarily took place through vegetative budding of new fronds from parent fronds. However, there occurs distinction both in size and longevity of plant body between generations. It may be expressed as cyclicity in the growth pattern of a colony [20, 29, 33]. The reproduction and growth pattern are found to be similar to microbial growth [34], and the doubling time is 20 to 24 h, which vary significantly among different species [35].

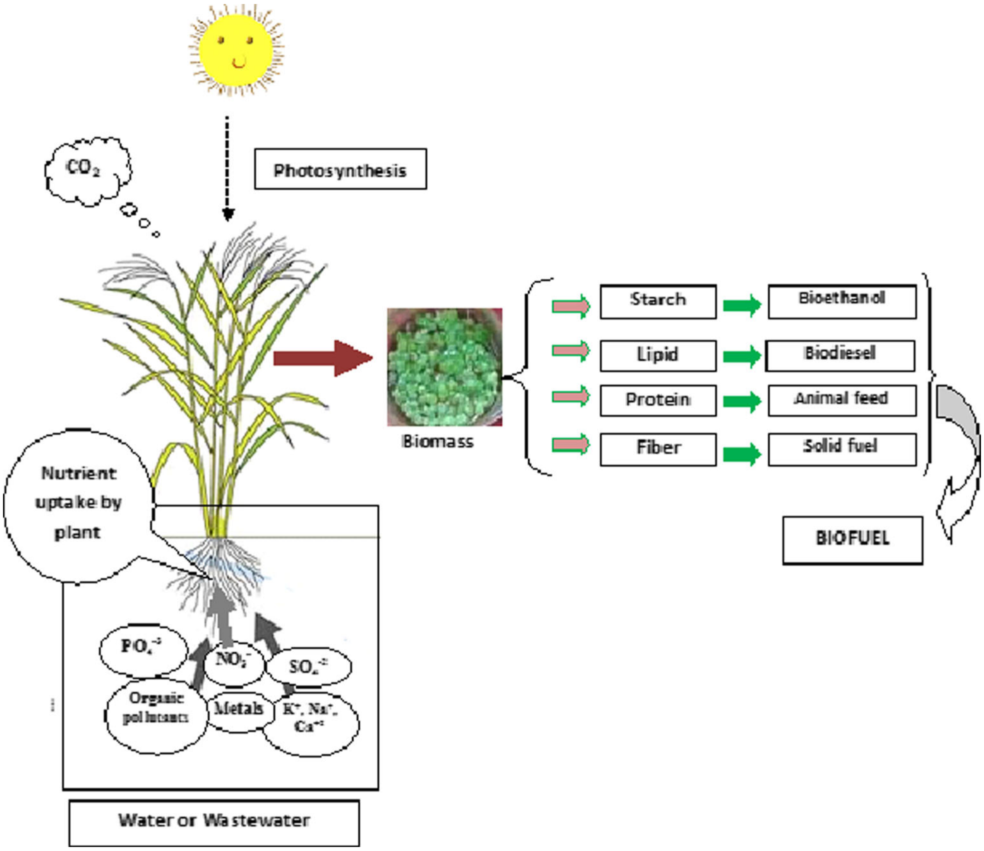
Potential of Duckweed Biomass in Renewable Energy Operations: Recent Approaches

The growing demand of energy can be dealt in best way by fostering the renewable energy technologies as long-term solution to energy problems mainly in developing countries [36] where conventional energy resources are either limited or explored indiscriminately. Plant resources especially non-edible plant species (wild plants, aquatic and terrestrial weeds, wetland plants, forest stand and their residues, etc.) can be a potential source of biomaterial and bioenergy. Not all plant biomass/products are suitable for energy generation in terms of energy values and outputs against invested cost in the energy harvesting technology. The chemistry is pivotal factor in determining the energy potential of any available biomass in energy production system. The biomass resources are the organic matters having chemical energy mainly synthesized through photosynthesis process in the presence of solar light [37]. Through complex metabolic activities, the plant synthesizes several active chemical ingredients which can be further harvested for biofuel purposes. So, in this process, the solar energy is stored in the forms of chemical bonds in plant biomass. The fixing of solar energy into bioenergy is illustrated in Fig. 1. The biochemical composition of duckweed as reported in scientific literature by various authors ensures the possibility of duckweed in renewable energy operations. The high rate of quality biomass (rich in carbohydrate, starch, protein and lipids) production in duckweeds advocates its utility in biomass-based biorefinery (Table 1). The quantity (dry weigh basis) of carbohydrate, starch, crude protein, crude fibre and lipid has been reported in the ranges of 17.6–35 %, 21–38 %, 16–41.7 %, 8.8–15.6 % and 4.5–9 %, respectively, by various researchers [24, 39–41]. However, concentration of lipid and starch seems comparatively lower in duckweed as compared to other plant biomasses that can be further enhanced considerably through plant growth conditions manipulations (like pH, temperature and nutrient concentration in culture substrates) [24, 40, 42–45]. The major constituents of carbohydrate in duckweed biomass are 20.3 % pectin (including galacturonan, xylogalacturonan, rhamnogalacturonan), 3.5 % hemicellulose (comprising xyloglucan and xylan) and 0.03 % phenolic compounds [46]. Lipid mainly comprises of long chain alcohol and acids and abundant in nitrogen contains compounds like pyrrole and indole [47]. In duckweed, the presence of few important fatty acids—palmitic acid, linoleic acid, linolenic acid and *p*-coumaric acid has been reported. Few authors have claimed the high content of palmitic acid and linoleic acid in duckweed biomass which can be further harvested for biodiesel production [48–50].

Traditionally, combustion had been utilized as major practice to harvest energy from dry biomasses. Apart from that other processes like anaerobic digestion, incineration, pyrolysis, gasification, oxidation, etc. are also used efficiently for energy resource recovery from plant biomass [38, 51]. The choice of mechanism to harvest energy from biomass is governed mainly by various factors: the type and quantity of biomass feedstock; the desired form of the energy, i.e. end-use requirements; environmental standards; economic conditions and project specific factors. The possible end products of biomass conversion processes are depicted in Fig 2. The quality of end products and their further processing is also concerned in terms of energy values of end products, total cost of operation and emission controls. The chemical characterization of available duckweed species has been estimated by various authors through proximate and ultimate analysis which suggests the feasibility of duckweed-based feedstock in other energy operations like pyrolysis, gasification, biogas, incineration, etc. [1, 24, 39, 42, 52].

The duckweed biomass can be converted into three main products: two related to energy—power/heat generation and transportation fuels—and one as a chemical feedstock [53]. Table 2 describes the multitude of techniques that can be employed in biomass energy resource recovery. But for optimum productivity of the duckweed-based energy units, the protocol for the maximum biomass harvesting and process design need to be explored and designed. Recently, few

Fig. 1 Fixation of solar energy into energy rich biomass



studies on optimization have claimed the enrichment of duckweed biomass with energy rich substances. Like alternation in physical environmental conditions and/or nutrient loads manipulations leads to fast metabolism of energy value substances in duckweeds. Studies have shown the starch contents in duckweed biomass in the ranges of 3 and 75 % (dry weight basis) under manipulated conditions [28–31]. Tao et al. [52] have studied the interrelationship between nutrients uptake and metabolic activities in duckweed *Landoltia punctata* and found that the quality of biomass enhances under starvation

Table 1 Techniques for biomass resource recovery [38]

Techniques	Cost of treatment	Environmental paybacks	Advancement require	Development stage	Remarks
Anaerobic digestion	Low/moderate energy	Biogas generation	Sludge pre-hydrolysis required to enhance biogas generation	Successfully applied at full-scale	Release of phosphate and ammonia during digestion process
Incineration	High	Energy generation minimization of biosolids quantity	Mechanical dewatering, drying, use of waste heat	Full-scale	Phosphate can be recovered from ash
Coincineration in coal fired power plant	High/moderate	Energy generation, beneficial use of inorganics	Mechanical dewatering, drying, use of waste heat	Full-scale	Relative amount that can be co-incinerated is limited
Pyrolysis and gasification	High	Valuable products recovery, minimization of biosolids quantity	Mechanical dewatering, drying, use of waste heat	In development stage	Complex process, marketing of products needs attention
Wet air oxidation	Moderate	Improvement in dewatering properties of sludge	Optimization	Applied globally in practice	Process primarily focused on sludge dewatering
Supercritical water oxidation	High	Energy generation, minimization of biosolids quantity	Reactor concept, process performance	In development stage	Complex process corrosion and scaling problems of the reactors walls
Hydrothermal treatment	Moderate	Biogas generation, production of valuable carbon resource or denitrification, minimization of biosolids quantity	Process performance	Practical experience limited	Removal of heavy metal can be included

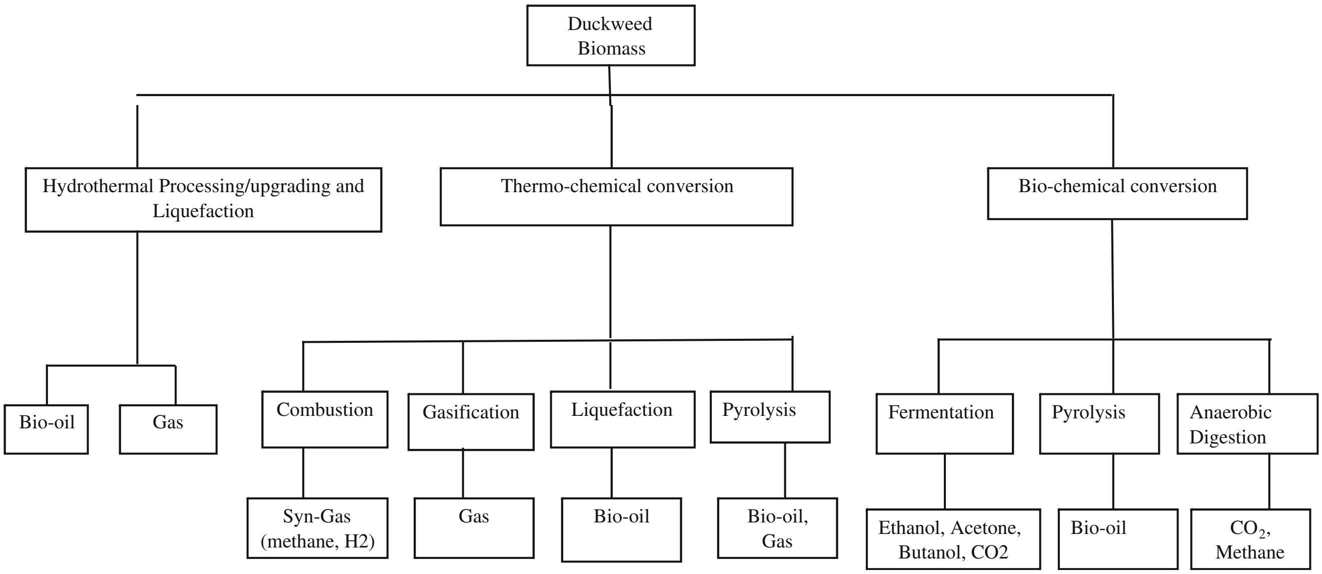


Fig. 2 Option to convert duckweed biomass into energy resources

conditions. The prolonged nutrient limitation regulates the different metabolic activities in plants. Data on transcriptomics, enzymatic assay and physiological characterization have revealed that the collaborative effect of enzyme regulating pathway helps in fast and high starch accumulation and low lignin percentage in aquatic weeds [59]. The load of nutrient in culture media also helps in chemical quality enhancement of weed biomass. Cheng and Stomp [24] recorded the increase in starch content (45.8 %) in duckweed *S. polyrrhiza* biomass when the plants were transferred from a nutrient rich solution (anaerobically treated swine waste) to a solution made up of tap water. The temperature is an important physical environmental condition which directly governs the metabolic process in plants. Cui et al. [42] have observed the increased starch accumulation in *S. polyrrhiza* cultured at low temperature (5 °C) than high temperature (with 15 and 25 °C) cultures.

The high starch content (≥75 %) in duckweeds is comparable to other starch rich crop, i.e. corn (starch ≥65 to 75 %) which is popularly being used in bioethanol production [60]. Few earlier workers have demonstrated that duckweed carbohydrate can be converted to ethanol and butanol efficiently [58, 59, 61]. Cheng and Stomp [24] have reported 25.8 % (of biomass) bioethanol produced though fermentation of duckweed-derived hydrolysates. *L. punctuate* has been reported as promising feedstock for bioethanol production as glucose yield in this plant is about 218.6±3.10 mg/g dry matter [61]. A study by Perniel et al. [61] has claimed 30.8±0.8 g/l ethanol production from *L. punctuate* biomass with 90.04 % fermentation efficiency using *Saccharomyces cerevisiae*. However, the starch yield in duckweed-based system is highly appreciated by few works. For example, Zhao et al. [41] have estimated, based on the accumulation rate of 2.06 g starch/m^2/d, an annual starch yield of 7.52 tons per hectare. Such high quantity of starch can be further utilized for bioenergy purposes. Ge et al. [56] have reported 20.3 % (*w*/*w*) total glucan and 32.3 % (*w*/*w*) proteins; trace hemicellulose and undetectable lignin in duckweed biomass harvested from wastewater. Their study further confirmed the release of about 96.2 % (*w*/*w*) glucose from both the cellulose and starch fractions of

Table 2 Biochemical composition of various duckweed species biomass (*DW*, dry weight basis)

Species	Dry matter (g/m^2 day)	Carbohydrate (DW %)	Crude protein (DW %)	Crude fibre (DW %)	Ash (DW %)	Lipid (DW %)	Reference
L. gibba	8.3	–	35	–	–		[54]
L. gibba	4.6	–	25.2	9.4	14.1	4.7	[55]
S. polyrhiza	5.1	–	29.1	8.8	15.2	4.5	[55]
L. minor	3.5	20.3	32.3	–	17.7	8.7	[56]
L. gibba	3.5	17.6	41.7	15.6	16.2	4.4	[21]
Lemna sp.	–	35	16	–	26	9	[57]
Landoltia punctata	–	24.5	16.27	–	3.48	–	[65]
Lemna sp.	–	25.7	35.1	11.9	16.5	3.4	[58]

biomass without prior thermal-chemical pre-treatment. These hydrolysates, fermented through two yeast strains (self-flocculating yeast SPSC01 and conventional yeast ATCC 24859, yielded ethanol of 0.485 g/g glucose [56].

The duckweed can be a potential source of feedstock in anaerobic digestion process which is utilized as major mechanism in biogas production. This process occurs in four main stages namely: hydrolysis, acidogenesis/fermentation, acetogenesis and methanogenesis, thereby require various groups of microbes to complete each of the stages [43]. Due to certain sets of limitations, the duckweed biomass cannot be utilized in a single feed in anaerobic digestion; therefore, the co-digestion of duckweed with any other conventional sludge can solve this issue. Few previous studies suggested the utility of duckweed biomass in anaerobic digestion to enhance the anaerobic process. Clark and Hillman [62] investigated the impact of adding iron rich duckweed as a supplement to chicken manure in batch and semi-continuous lab-scale anaerobic digesters. The results validated an increased gas production rate of about 44 %. Undergoing anaerobic digestion, the accumulated biomass can be used as a source of energy and at the same time the digestate can be used as a low quality feed or a soil conditioner.

The thermochemical conversion (gasification, liquefaction and pyrolysis) of weed biomass also produces few products of benefits. The utility of duckweed biomass in gasification processes is less studied due to several shortfalls associated with these processes. Pyrolysis is another major biochemical conversion process which is significantly studied by various authors in case of duckweed biomass. The major gaseous products of duckweed pyrolysis are H_2, CO, CO_2 and CH_4, with minute amounts of C_2H_6 and C_2H_4 hydrocarbons. However, in this process, the CO_2 was regarded as a major component of the gaseous mixture amounting to about 60 vol% [48] which can be harnessed for energy purposes. The liquefaction process yields in some products of energy values. But liquefied oil obtained from liquefaction process contains high carbon and hydrogen content and low nitrogen content than the oil obtained through pyrolysis process [63]. So, in this process, there is possibility of upgrading process in order to maximize the quality yield of the system. Duan et al. [57] in their study upgraded the liquefaction process coupling it with pyrolysis system to convert *Lemna* sp. biomass into alternative energy products. Temperature and retention time are important factors in the completeness of the thermochemical liquefaction process. Temperature range between 260–340 °C increases oil yield, and the process get completed within 60 min even in the absence of catalyst [58]. The elemental composition of obtained liquefied oil is reported as 73 % carbon, 9 % hydrogen and 5 % nitrogen with average heating value of 34 MJ/kg [56]. Thus, properties of this oil were very similar to that of liquefied oil obtained from manure. The slow thermolysis of duckweed biomass results in 10.7 % of the bioleum, 45.0 % of char and 19.44 % of gases [62]. Muradov et al. [64] has also reported yield of 38 % bio-oil, 44 % char and 17 % gas during slow pyrolysis of *L. minor* (at higher reaction temperatures of 500 °C) biomass. The physico-chemical properties of bio-oils derived from duckweed through hydrothermal processing were dark-brown, viscous and with smoky odour. Few other workers have reported the heating values of duckweed oils around 32–36 MJ/kg, which seems slightly lower than the petroleum-derived fuels (42 MJ/kg) [61, 65]. Biochar is another value-added product obtained from duckweed biomass. Biochar acts by enhancing moisture retention and nutrient holding capacity of the soil (which means less dependence on chemical fertilizers). The pyrolysis temperature and sweep

Table 3 Bioenergy production from different species of duckweed biomass

Species	Treatment	Product	Remarks	Reference
Lemna minuta	Photosynthetic plant fuel cell	Electricity	Current and power density up to 1.62±0.10 A.m^{-2} and 380±19 mW.m^{-2}, respectively, were achieved under sunlight conditions	[67]
Lemna gibba	Thermochemical pyrolysis	Bio-oil	Bio-oil components can potentially be used for the production of ‘green’ gasoline and diesel fuel	[64]
Lemna minor	Hydrolysis and fermentation	Bioethanol	High bioethanol yield of 0.485 g g^{-1} (glucose)	[56]
Lemna spp.	Thermochemical liquefaction	Bio-oil	Average heating value=34 MJ/kg	[58]
Lemna minor	Thermochemical pyrolysis	Biochar	Biochar exhibited catalytic activity in biogas reforming	[64]
Spirodela polyrrhiza	Hydrolysis and fermentation	Bioethanol	Annual starch yield 9.42×10^3 kg ha^{-1} and ethanol yield of 6.42×10^3 l ha^{-1}	[39]
Lemna minor	Thermochemical pyrolysis	Gas, bio-oil and char	Pyrolysis temperature had minor effect on the bio-oil product, and residence time had negligible effect on the yield and composition of the duckweed pyrolysis products	[47]
Lemna minor	Pre-treatment and fermentation	Bioethanol	Ethanol yield=258 mg/g (DW)	[68]
Wolffia and *Spirodela* species	Thermolysis	Bioleum	Bioleum with lower oxygenate levels and higher heating values	[47]

gas flow rate determines the yield of *L. minor* derived biochar by changing pore development pattern, surface area and textural characteristics [66].

Apart from the chemically rich, the duckweed is one of the fastest growing weeds which make this as suitable candidate for rich biomass production. A small plant size, limited life cycle, high duplication rate, adequacy to grow on different culture medium and lack of waxy cuticle (to prevent water loss) of the duckweed are few of the characteristics that have been used to evaluate the efficiency of biomass generation and ensure its utility as bioenergy feedstock [38]. Duckweed biomass has a high surface area to volume ratio that obviates the need for biomass milling or grinding, also absence of waxy cuticle quantified water availability in biomass. Both of these characteristics enhance duckweed as a viable biomass option as it can be dried quickly with low energy inputs. Table 3 depicted the bioenergy potential of harvested duckweed biomass.

It is therefore suggested that conversion of duckweed biomass into renewable energy bioresources is an important carbon-negative technology. The duckweed plant represents an attractive non-food aquatic crop that has a high potential to turn nutrients from wastewater to economically sound bioenergy feedstock, which can further transform into a biofuel/biogas/biochar. It can be used as a promising alternative feedstock for bioenergy production.

Biomass-Based Energy Production and Duckweed: Challenges and Opportunities

Bioenergy production is considered to be an ecologically attractive option. The sustainability of bioenergy production processes with respect to ecological services and land use, emissions, resource efficiency and waste management is often a critical issue to deal with [1, 69]. The use of conventional energy crops and trees (*Miscanthus*, *Jatropha*, *Salix*, *Panicum*, *Eucalyptus*, etc.) will pose serious ecological challenges such as loss of biodiversity, loss of natural habitats and wildlife and soil degradation [10, 17]. The increase in biomass for energy plantation will reduce the amount of land available for agriculture. This situation is aggravated in recent years due to unparalleled government incentives to agriculture and bioenergy, favouring the latter. Additionally, the requirement for water resources and land availability also creates problem [1, 17].

The use of aquatic plant duckweed diminishes the possibility of any shortfalls. Relying on duckweed biomass for bioenergy could be associated with carbon neutral process and provides numerous benefits related to energy security, economics and the environment [70]. The integration of wastewater remediation using duckweed species not only mainstreams water resource availability but also results in accumulation of abundant biomass [58]. This biomass can be further harvested to see its utility in bioenergy productions. Utilization of duckweed substrates as raw materials for bioenergy should minimize the potential conflict between food and fuel as these can withstand and offer a viable option in place of recently used bioenergy feedstock which are mostly food-industry based (such as corn) [10]. Besides having several benefits, the production and utilization of duckweed feedstock also admit several challenges that need to get target for better resource utilization. An improved biomass collection network and storage is the main challenge for the establishment of commercial bioenergy feedstock platform [57]. Transportation, storage and logistic requirements need address for economically viable bioenergy production. The inconsistencies in quality and quantity of duckweed produced, moisture content of duckweed materials may also contribute to unproductive conversion processes [70]. The technological improvements could help to improve the system efficiency and provide value-added co-products, which will reduce the production cost [43]. It can be concluded that a critical evaluation has been needed to address various issues regarding selection of any process for the bioconversion of substrates [24, 39]. The realization of current research challenges helps to mainstream the production of bioenergy using abundant duckweed biomass. It is important to derive primary cost-benefit analysis to ensure the practicability of this novel technology [71]. The feasibility aspects help to enhance the energy balance and also reducing the emissions and production costs, to become true alternatives that complete the biomass-based energy future scheme [39]. The by-products resulting from various conversion methods (such as hydrothermal processing/upgrading and liquefaction, thermochemical and biochemical conversion) may result in environmental problem and therefore need to be properly disposed of [47]. The fate of phosphorus present in biomass is unanswerable as it remains in the processed solids residue and liquid stream. The additional research helps to reveal the efficient ways to deal with relevant problems associated with treatment before disposal. The characterization of waste products obtained will be helpful to analyse the recovery, reuse and recycle option.

Conclusions

Energy demands will aggravate with time in this fast growing industrial society. The use of biomass for bioenergy purpose will provide a competent option towards meeting energy needs. Various plant species (food and non-food) are accounted for this purpose; however, their utilization depends on availability, growth dynamics, etc. Also, the associated food crisis equally demarks their use as potential energy feedstock. The use of aquatic plant duckweed represents an attractive non-food plant that can be efficiently utilized for bioenergy production. The integrated duckweed-based treatment system supported with wastewater will bring significant environmental benefits (such as water purification, biomass generation) and seems to be an ecologically friendly and cost-effective solution for water pollution and bioenergy-based feedstock production. The harvested plant showcases significantly high content of crude protein, amino acids, starch and lower content of fibre. These biochemical characteristics of duckweed supported their candidature for excellent feedstock for bioenergy production. The varieties of products were reported to be produced from duckweed such as biofuel, biogas, biochar, etc. This advocates that a plant has huge potential towards nutrient recovery and its conversion to efficient energy resource. The available feedstock is cost-supportive, easily harvestable and can be processed into energy form efficiently.

References

1. Mafakheri F, Nasiri F (2014) Modeling of biomass-to-energy supply chain operations: applications, challenges and research directions. Energy Policy 67:116–126
2. Spalding-Fecher R, Williams A, van Horen C (2000) Energy and environment in South Africa: charting a course to sustainability. Energy Sustain Dev 4:8–17
3. Johansson B (2013) Security aspects of future renewable energy system: a short overview. Energy 61:598–605
4. Siirola JJ (2014) Speculations on global energy demand and supply going forward. Curr Opin Chem Eng 5:96–100
5. Lohan SK, Dixit J, Modasir S, Ishaq M (2012) Resource potential and scope of utilization of renewable energy in Jammu and Kashmir, India. Renew Energy 39:24–29
6. Ellabban O, Abu-Rub H, Blaabjerg F (2014) Renewable energy resources: current status, future prospects and their enabling technology. Renew Sust Energ Rev 39:748–764
7. Asif M, Muneer T (2007) Energy supply, its demand and security issues for developed and emerging economies. Renew Sust Energ Rev 11:1388–1413
8. Armor JN (2014) Key questions, approaches, and challenges to energy today. Catal Today 236:171–181
9. Ashnani MHM, Johari A, Hashim H, Hasan E (2014) A source of renewable energy in Malaysia, why biodiesel? Renew Sust Energ Rev 35:244–257
10. Baratieri M, Baggio P, Fiori L, Grigiante M (2008) Biomass as an energy source: thermodynamic constraints on the performance of the conversion process. Bioresour Technol 99:7063–7073
11. IEA (2010) Energy balances of non-OECD countries. International Energy Agency, Paris
12. Gupta VK, Potumarthi R, O'Donovan A, Kubicek CP, Sharma GD, Tuohy MG (2014) Chapter 2 – Bioenergy research: an overview on technological developments and bioresources. Bioenergy Res Adv Appl 23–47
13. Utamaa NA, Fathonia AM, Kristiantoa MA, McLellan BC (2014) The end of fossil fuel era: supply–demand measures through energy efficiency. Procedia Environ Sci 20:40–45
14. Cherubini F, Bird ND, Cowie A, Jungmeier G, Schlamadinger B, Woess-Gallasch S (2009) Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: key issues, ranges and recommendations. Resour Conserv Recycl 53:434–447
15. Venturi P, Venturi G (2003) Analysis of energy comparison for crops in European agricultural systems. Biomass Bioenergy 25: 235–255
16. Solomon BD (2010) Biofuels and sustainability. Ann N Y Acad Sci 1185:119–134
17. Awudu I, Zhang J (2012) Uncertainties and sustainability concepts in biofuel supply chain management: a review. Renew Sust Energ Rev 16:1359–1368
18. Sims REH, Hastings AT, Schlamadinger B, Taylor G, Smith P (2006) Energy crops: current status and future prospects. Glob Chang Biol 12:2054–2076
19. Mari S, Antti L, Jukka R (2013) Screening of novel plants for biogas production in northern conditions. Bioresour Technol 139: 355–362
20. Wang W (1990) Literature review on duckweed toxicity testing. Environ Res 52:7–22
21. Skillicorn P, Spira W, Journey W (1993) Duckweed Aquaculture. A new aquatic farming system for developing countries. The World Bank, Washington, DC
22. Vymazal J (2011) Plants used in constructed wetlands with horizontal subsurface flow: a review. Hydrobiologia 67:4133–4156
23. Sawangkeawa R, Ngamprasertsith S (2013) A review of lipid-based biomasses as feedstocks for biofuels production. Renew Sust Energ Rev 25:97–108
24. Cheng JJ, Stomp A (2009) Growing duckweed to recover nutrients from wastewaters and for production of fuel ethanol and animal feed. Clean Soil Air Water 37:17–26
25. Verma R, Suthar S (2014) Synchronized urban wastewater treatment and biomass production using duckweed *Lemna gibba* L. Ecol Eng 64:337–343
26. Bal-Krishna KC, Polprasert C (2008) An integrated kinetic model for organic and nutrient removal by duckweed-based wastewater treatment (DUBWAT) system. Ecol Eng 34:243–250
27. Papadopoulos FH, Tsihrintzis VA (2011) Assessment of a full-scale duckweed pond system for septage treatment. Environ Technol 32: 795–804
28. Les DH, Crawford DJ, Landolt E, John D, Gabel JD, Rebecca KT (2002) Phylogeny and systematics of Lemnaceae, the duckweed family. Syst Bot 27(2):221–240
29. Landolt E, Kandeler R (1987) The family of Lemnacae—a monographic study. Vol 2. Part of the series: biosystematic investigations in the family of duckweeds (Lemnacae), vol 3 of 4. *Veroffentlichungen Des Geobotanischen (pub.)*
30. Landolt E (1992) Lemnaceae Duckweed Family Vascular Plants of Arizona. J Ariz Nev Acad Sci 1:10–14
31. Hillman SW (1961) The Lemnaceae or duckweeds. A review of the descriptive and experimental literature. Bot Rev 27:221–287
32. Ashbey E, Wangermann E (1949) Senescence and rejuvenation in *Lemna minor*. Nature 31:164–187
33. Blackburn KB (1933) Notes on the chromosomes of the duckweeds (Lemnaceae) introducing the question of chromosome size. Proc Univ Dur-Ham Phil Soc 9:84–90
34. Goopy PJ, Murray JP (2003) A review on the role of duckweed in nutrient reclamation and as a source of animal feed. Asian-Aust J Anim Sci 16:297–305
35. Chang SM, Yang CC, Sung SC (1977) The cultivation and the nutritional value of Lemnaceae. Bull Inst Chem Acad Sin 24:19–30
36. Kumar A, Kumar K, Kaushik N, Sharma S, Mishra S (2010) Renewable energy in India: current status and future potentials. Renew Sust Energ Rev 14:2434–2442
37. Saxena RC, Adhikari DK, Goyal HB (2009) Biomass-based energy fuel through biochemical routes: a review. Renew Sust Energ Rev 13:167–178
38. Rulkens WH, Bien JD (2004) Recovery of energy from sludge-comparison of the various options. Water Sci Technol 50:213–221

39. Xu J, Zhao H, Stomp AM, Cheng JJ (2012) The production of duckweed as a source of biofuels. Biofuels 3:589–601
40. Xiao Y, Fang Y, Jin Y, Zhang G, Zhao H (2013) Culturing duckweed in the field for starch accumulation. Ind Crop Prod 48:183–190
41. Zhao Y, Fang Y, Jin Y, Huang J, Bao S, Fu T, He Z, Wang F, Zhao H (2014) Potential of duckweed in the conversion of wastewater nutrients to valuable biomass: a pilot-scale comparison with water hyacinth. Bioresour Technol 163:82–91
42. Cui W, Xu J, Cheng JJ, Stomp AM (2010) Growing duckweed for bio-ethanol production. ASABE Paper No. 1009440. 7 p
43. Campanella A, Muncrief R, Harold MP, Griffith DC, Whitton NM, Weber RS (2012) Thermolysis of microalgae and duckweed in a CO2-swept fixed-bed reactor: bio-oil yield and compositional effects. Bioresour Technol 109:154–162
44. Liu Y, Fang Y, Huang M, Jin Y, Sun J, Tao X, Zhang G, He K, Zhao Y, Zhao H (2015) Uniconazole-induced starch accumulation in the bioenergy crop duckweed (*Landoltia punctata*) I: transcriptome analysis of the effects of uniconazole on chlorophyll and endogenous hormone biosynthesis. Biotechnol Biofuels 8:57
45. Liu Y, Fang Y, Huang M, Jin Y, Sun J, Tao X, Zhang G, He K, Zhao Y, Zhao H (2015) Uniconazole-induced starch accumulation in the bioenergy crop duckweed (*Landoltia punctata*) II: transcriptome alterations of pathways involved in carbohydrate metabolism and endogenous hormone crosstalk. Biotechnol Biofuels 8:64
46. Su H, Zhao Y, Jiang J, Lu Q, Li Q, Luo Y, Zhao H, Wang M (2014) Use of duckweed (*Landoltia punctata*) as a fermentation substrate for the production of higher alcohols as biofuels. Energy Fuels 28:3206–3216
47. Muradov N, Taha M, Miranda AF, Kadali K, Gujar A, Rochfort S, Stevenson T, Ball AS, Mouradov A (2014) Dual application of duckweed and azolla plants for wastewater treatment and renewable fuels and petrochemicals production. Biotechnol Biofuels 7:30
48. Gui MM, Lee KT, Bhatia S (2008) Feasibility of edible oil vs. non-edible oil vs. waste edible oil as biodiesel feedstock. Energy 33:1646–1653
49. Carmo AC Jr, de Souza LKC, da Costa CEF, Longo E, Zamian JR, Filho GNR (2009) Production of biodiesel by esterification of palmitic acid over mesoporous aluminosilicate Al-MCM-41. Fuel 88:461–468
50. Singh SP, Singh D (2010) Biodiesel production through the use of different sources and characterization of oils and their esters as the substitute of diesel: a review. Renew Sust Energ Rev 14:200–216
51. Long H, Li X, Wang H, Jia J (2013) Biomass resources and their bioenergy potential estimation: a review. Renew Sust Energ Rev 26:344–352
52. Tao X, Fang Y, Xiao Y, Jin Y, Ma X, Zhao Y, He K, Zhao H, Wang H (2013) Comparative transcriptome analysis to investigate the high starch accumulation of duckweed (*Landoltia punctata*) under nutrient starvation. Biotechnol Biofuels 6:72
53. McKendry P (2002) Energy production from biomass (part 2): conversion technologies. Bioresour Technol 83:47–54
54. Mohedano RA, Rejane HR, Tavares FA, Filho PB (2012) High nutrient removal rate from swine wastes and protein biomass production by full-scale duckweed ponds. Bioresour Technol 112:98–104
55. Rusoff LL, Blakney EW, Culley DD (1980) Duckweeds (Lemnacae Family): a potential source of protein and amino acids. J Agric Food Chem 28:848–850
56. Ge X, Zhang N, Phillips GC, Xu J (2012) Growing *Lemna minor* in agricultural wastewater and converting the duckweed biomass to ethanol. Bioresour Technol 124:485–488
57. Duan P, Chang Z, Xu Y, Bai X, Wang F, Zhang L (2013) Hydrothermal processing of duckweed: effect of reaction conditions on product distribution and composition. Bioresour Technol 135:710–719
58. Xiu SN, Shahbazi A, Croonenberghs J, Wang LJ (2010) Oil production from duckweed by thermochemical liquefaction. Energy Sources A 32:1293–1300
59. Huang M, Fang Y, Xiao Y, Sun J, Jin Y, Tao X, Ma X, He K, Zhao H (2014) Proteomic analysis to investigate the high starch accumulation of duckweed (*Landoltia punctata*) under nutrient starvation. Ind Crop Prod 59:299–308
60. Choy B, Reible DD (2000) Diffusion models of environmental transport. Lewis, Boca Raton
61. Perniel M, Ruan R, Martinez B (1998) Nutrient removal from a stormwater detention pond using duckweed. Appl Eng Agric 14:605–609
62. Clark PB, Hillman PF (1996) Enhancement of anaerobic digestion using duckweed (*Lemna minor*) enriched with iron. Water Environ J 10:92–95
63. Ramírez F, Seco A (2011) Minimizing the environmental effects caused by the production of bioenergy. Renew Sust Energ Rev 15:3327–3331
64. Muradov N, Fidalgo B, Gujar AC, T-Raissi A (2010) Pyrolysis of fast-growing aquatic biomass—*Lemna minor* (duckweed): characterization of pyrolysis products. Bioresour Technol 101:8424–8428
65. Chen Q, Jin Y, Zhang G, Fang Y, Xiao Y, Zhao H (2012) Improving production of bioethanol from duckweed (*Landoltia punctata*) by pectinase pretreatment. Energies 5:3019–3032
66. Liao R, Gao B, Fang J (2013) Invasive plants as feedstock for biochar and bioenergy production. Bioresour Technol 140:439–442
67. Hubenova Y, Mitov M (2012) Conversion of solar energy into electricity by using duckweed in direct photosynthetic plant fuel cell. Bioelectrochemistry 87:185–191
68. Bayrakci AG, Koçar G (2014) Second-generation bioethanol production from water hyacinth and duckweed in Izmir: a case study. Renew Sust Energ Rev 30:306–316
69. Zhu MT, Feng WY, Wang B, Wang TC, Gu YQ, Wang M (2008) Comparative study of pulmonary responses to nano- and submicron-sized ferric oxide in rats. Toxicology 247:102–111
70. Kurian JK, Nair GR, Hussain A, Raghavan GSV (2013) Feedstocks, logistics and pre-treatment processes for sustainable lignocellulosic biorefineries: a comprehensive review. Renew Sust Energ Rev 25:205–219
71. Rao PV, Baral SS, Dey R, Mutnuri S (2010) Biogas generation potential by anaerobic digestion for sustainable energy development in India. Renew Sust Energ Rev 14:2086–2094