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REVIEW ARTICLE

Duckweed-based clean energy production dynamics (ethanol and biogas) and phyto-remediation potential in Bangladesh

Kamrun Nahar[1] · Sanwar A. Sunny[2]

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Abstract
This paper presents an overview of the prospect of biofuel resources in Bangladesh with second-generation (2G) aquatic energy crop—Duckweed. The review sheds light on growing duckweed as a promising feedstock to produce ethanol and biogas, as they can minimize dependence on limited crude oil and natural gas—fossil fuels that Bangladesh largely depends on. Current reserves are inadequate to meet the energy demand for long term economic growth. Biofuels, as nontoxic and biodegradable alternatives, could replace harmful fossil fuels as combustion of biofuel emits considerably less amount of CO_x, SO_x, hydrocarbons and particulate matter. Bangladesh has millions of hectors of potential sites across lakes, rivers and ponds, which can conduct high rates of nutrient uptake via phytoremediation, such as Nitrogen and Phosphorus, in industrial wastewater, and then be used to produce biofuels. The review explores different production processes and briefly charts future research agenda for the proliferation of clean energy in Bangladesh using locally available products.

Keywords Bangladesh · Clean energy · Duckweed biomass · Biofuel · Ethanol · Biogas · Phytoremediation

Introduction

Energy consumption has been increasing worldwide due to increasing population growth, rapid urbanization and industrialization. Fossil fuels, such as coal, crude oil and natural gas, are currently the predominant energy sources. However, crude oil and natural gas are limited resources that will be depleted in the near future. Although there are debates about the exact year of peak oil production, it is generally believed that it will occur before 2025, after which a decline in worldwide crude oil production will begin (Campbell 2013). The annual global oil production would decline from the current 25 billion barrels to approximately five billion barrels in 2050 (Campbell and Laherrere 1998). An increasing demand for energy and the inevitable depletion of fossil fuels has stimulated exploration for alternative energy sources.

✉ Kamrun Nahar
nahar.kamrun@northsouth.edu

Sanwar A. Sunny
ssunny@ubalt.edu

[1] Department of Environmental Science and Management, North South University, Dhaka, Bangladesh

[2] Merrick School of Business, University of Baltimore, Baltimore, Maryland, USA

Bio-based renewable energy is an important energy alternative that can reduce world dependence on fossil-based fuels (Nahar and Sunny 2011). Unlike fossil fuels, biofuels, such as bioethanol is a renewable energy source produced through fermentation of sugars, and as such a potential alternative to petroleum-derived fuels, for example those used in transportation. Biofuels utilize the concept of carbon neutrality to create useful fuels for the transportation sector (Sunny 2017). Plant biomass feedstock requires CO_2 for photosynthesis process, absorbing it from the environment for metabolic use. Scholars agree that developing biofuels from renewable feedstock would provide environmental and social benefits (Lynd et al. 1991; Wyman 1994; Nahar 2011). The production of bioethanol and its consumption as a fuel could substantially lower CO_2 emissions compared with those from fossil fuels. The production of renewable biomass and its conversion to bioethanol or biogas could also generate jobs for local communities, especially those specializing in agriculture (Nahar 2012). In other words, biofuels obtained from biomass can be promising alternatives to fossil fuels to reduce the greenhouse gas emissions and meet the strong global demand for energy.

Bioethanol is mainly produced on an industrial scale from feedstocks containing starch and sugar, such as corn in the United States and sugarcane in Brazil (Sanchez and Cardona, 2008). Although lignocellulosic biomass is regarded as a promising feedstock for ethanol production, there are still several obstacles. For example, the lack of an efficient, economical and environmentally friendly pretreatment process limits economically feasible ethanol production (Sarkar et al. 2012). Ethanol production modes have additional barriers, particularly around food security and agricultural land insufficiency (Ge et al. 2011; Nahar 2011). Similar dilemma also exists in the production of ethanol using other feedstocks containing carbohydrates, for instance, sweet potato and cassava (Papong and Malakul 2011; Zhang et al. 2010). Recently research has thus focused on aquatic plants which can produce renewable fuels like bioethanol or biogas, with additional phytoremediation potential associated with wastewater treatment capabilities (Nahar 2012). In other words, Duckweed offers the promise of co-benefits of combining water purification with biofuel production for greater net environmental benefits.

Exploring new alternative feedstocks to produce green energy as biofuel is considered as an urgent topic, especially in Bangladesh where a number of edible and non-edible biofuel feedstock is available. However, edible sources are not promising as they need arable lands for cultivation (Nahar et al. 2011). But duckweed, a rapidly growing, high-yield aquatic plant can be the most effective source of clean energy which does not need arable land yet possesses high productivity with high lipid and starch contents. As such, it is a second-generation aquatic energy crop which can be used for the production of biofuel and is not used for human consumption (Sims et al. 2010). Since it can be produced in fresh water, saltwater and even in wastewater, and that Bangladesh has about 1.383 million hectares of water areas (lakes, rivers, costal saline water etc.) and 0.31 million hectares of ponds, biofuel production from duckweed can be viable decarbonization strategy. The advantages of this aquatic plant include high rates of nutrient uptake, such as Nitrogen and Phosphorus, making it viable in industrial wastewater treatment and phytoremediation strategies for wastewater alongside energy-based duckweed cultivation which may reduce the biofuel production costs.

Duckweeds as high-yield biomass feedstock

Duckweeds are monocotyledons, rapidly growing and free floating, flowering perennial aquatic plants, belonging to the Lemnaceae family. It is widely available in Bangladesh and classified into five genera viz. *Lemna, Spirodela, Wolffia, Landoltia* and *Wolffiella,* among which 40 species have been identified so far. They have long production period than most other plants, growing year-round in some areas with subtropical climate (Chaiprapat et al. 2005). The mentioned plants combine to form a green carpet on the surface of water. Each plant consists of 1–3 rounded leaf-like body usually not exceeding 0.5 cm in diameter floating on the surface with a slender root system. They float on still or slow moving fresh or wastewater (Oron et al. 1986) in subtropical climate (Vidal 2010). Several duckweed species have been examined for large-scale practical cultures or lab-scale experiments for biofuel production and nutrient removal from wastewater, although production differs depending on species (Zhao et al. 2014; Ziegler et al. 2015; Soda et al. 2015). In addition, it is a good resource of starch and proteins, which can be used for animal feed and production of liquid fuel ethanol (Zhang et al. 2010). Also accumulates biomass at more rapid rates than other higher plants, including agricultural crops (Landolt et al. 1987). The plant can grow in all seasons in areas of warm climate under the optimum condition (Xu et al. 2011; Peng et al. 2007) and depending on species and growing conditions, such as temperature, humidity etc., duckweeds can contain anywhere from 3 to 75% (dry-based) starch (Reid and Bieleski 1970; Landolt and Kandeler 1987a, b).

In context of Bangladesh, the plant can be grown abundantly with minimum cost and can be made available in much cheaper price than other alternative plant sources (Sunny 2011). It could be utilized to produce liquid fuel as ethanol and gaseous fuel as biogas. As source of clean energy, it is a promising, high-yield alternative energy sources to minimize or reduce dependence on limited crude oil and natural gas in the country. Besides the advantages of this aquatic plant also include high rate of nutrients uptake from wastewater, due to characteristics that include rapid growth rate, high biomass production potential, low lignin content and the ease of harvesting, processing etc. The plant usually proliferates through vegetative budding of new fronds from the leaf-like thallus (Landolt 1986). It has a doubling time of 2–7 days (Oron et al. 1986; Landolt et al. 1987; Xu et al. 2011). However, under ideal conditions, with a doubling time of 20–24 h (Körner et al. 1998). It has also been widely used in environmental biotechnology, such as municipal and industrial wastewater treatment and phytoremediation (Ge et al. 2011; Papong and Malakul 2011) in many countries including Bangladesh, Israel and the USA (Oron 1994; van der Steen et al. 1998).

Duckweed could produce a large quantity of biomass compare to other biomass resources and displace fossil fuel demand for end-uses, especially in countries with an agri-focused history. The annual yields of the duckweed species ranged from 20.4 to 54.8 t/ha in (DM) dry matter (Edwards et al. 1992; Oron 1990), whereas the yields of corn and corn sover are 5.22–7.66 t/ha, respectively (FAO 2012; Perlack and Turhollow 2003). Although its size does not typically hamper motor operations through rotor, or oar movement, it can obstruct water travel as a nuisance. It makes sense to remove, not only to regularly discard, but make useful utilization of this rapidly grown nuisance for dual benefits. Figure 1 and 2 shows fresh and dried duckweed (lemna strain, of Lemnoideae sub-classification) at the laboratory.

Starch characterization and production of ethanol

Duckweed, as a potential biofuel feedstock does not require the use of farmable land (Vidal 2010). Duckweed can be naturally found most prevalent in fresh or wastewater and wetlands. Its ability to grow in wastewaters with high nutrient concentration relative to other bodies of water, such as fresh water or wetlands (Cu et al. 2015) makes it a good candidate for feedstock. Industrial production of duckweed need not overtake freshwater lakes or rivers and could instead be limited to the many wastewater facilities located throughout developing nations. The starch content of duckweed can be significantly improved by changing the growth conditions, up to the amount of starch that is comparable to corn analysis by up to six times higher (Xu et al. 2011).

Fresh duckweed fronds contain from 92 to 94% water. Fiber and ash content is higher and protein content is lower in duckweed colonies with slow growth. The dried biomass shows high content of energy molecules with total sugar (38.0%), starch (24.5%), and lipid (9.3%) (Verma and Suthar 2016). The solid fraction of a wild colony of duckweed growing on nutrient-poor water typically ranges from 15 to 25%, protein and from 15 to 30% fiber. Duckweed grown under ideal conditions and harvested regularly will have a fiber content of 5 to 15% and a protein content of 35 to 45%, depending on the species involved. (Skillicorn et al. 1993).

Conversion of biomass to fuel power involves many steps from cultivation, harvest, and transport to actual production of biomass as feedstock to final product of usable fuel. The production process is dependent on many different properties of the source ingredient, such as cellulose concentration, sugar concentration, and starch concentration etc. Duckweed has a very high starch concentration ranging anywhere from 3 to 75%, depending on the species and growing conditions (Cui and Cheng 2015) and compounded as one of the fastest growing aquatic plants, it can effectively double biomass every 20 h (usually 16 h to 2 days), under appropriate and optimal environmental conditions (Cui and Cheng 2015; Peng et al. 2007; Xu et al. 2011). Figure 3 shows propagation of biomass under lab conditions.

Production of bioethanol, biogas and byproducts

Duckweeds are positioned to be ideal feedstock for the production of biofuels, especially ethanol (Chen et al. 2012; Fujita et al. 2016; Ge et al. 2012; Soda et al. 2015; Xu et al. 2011, 2012). This is due to their soft biomass and high starch content that can be easily and effectively saccharified to glucose (Lee et al. 2016). The production of bioethanol from lignocellulosic biomass basically involves four main steps: pretreatment, enzymatic-acidic hydrolysis, fermentation and distillation. A schematic skeleton of ethanol production

Fig. 1 Duckweed (Lemna Strain) cultivation at the laboratory

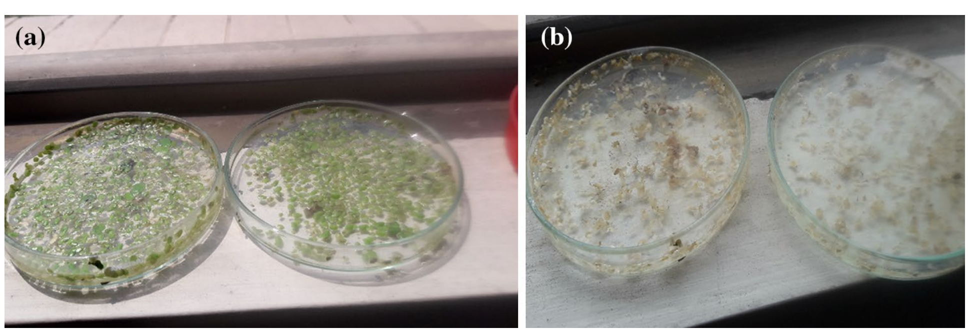


Fig. 2 **a** Fresh duckweed and **b** dried duckweed (formed due to removal of water) at the Laboratory

Fig. 3 Lab cultivation and propagation to show rapid growth. The left two images are shown at 4 weeks after cultivation, wherease the two right were after two additional weeks (6 weeks since cultivation)

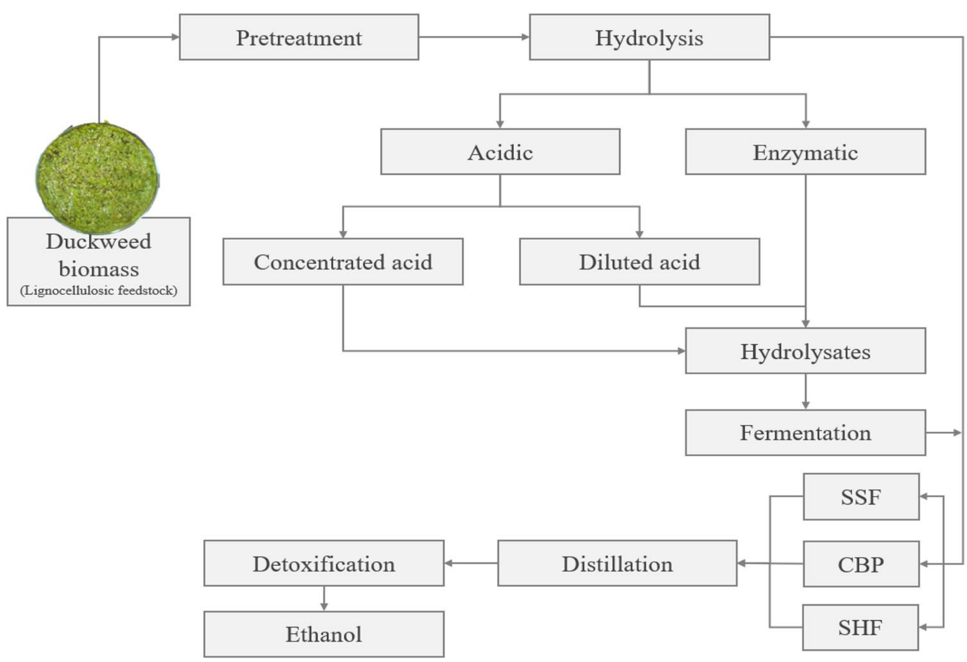
from duckweed shown below. First, it consists of production feedstock and harvest of biomass, containing accumulated high starch in the feedstock. After pre-treatment, enzymatic/acidic hydrolysis is the next step, which can be converse by fermentation to the ethanol. Fermentation could be done by either SSF (Simultaneous Scarification and fermentation), SHF (Separate hydrolysis and Fermentation) or CBP (consolidated bioprocessing). The hydrolysate is fermentable monomeric glucose sugars and can be fermented by microorganisms such as yeast (Saccharomyces cerevisiae). Ethanol fermentation is carried out in bioreactors in absence of oxygen at 30 ± 1 °C for 72 h.

$$\text{Glucose}(C_6H_{12}O_6) \xrightarrow{\text{Fermentation}} \text{Ethyl alcohol}(C_2H_5OH) + CO_2$$

The next and last step is distillation for separation of ethanol as the desired product. A simple flow chart from the feedstock to the ethanol biofuel is shown in Fig. 4. Duckweed carbohydrates could be converted to simple sugars for fermentation before bioethanol can be produced. The species Lemna minor contains high carbohydrates compare to others (Kabir et al. 2009). The carbohydrates found in dried duckweed are broken down into simple sugars by a process called saccharification (Xu et al. 2011). Enzymatic hydrolysis of this biomass yields a hydrolysate with high volume of reducing sugar. Bioethanol is produced by microbial fermentation of glucose, usually with the help of yeasts (e.g. Saccharomyces cerevisiae) as production microorganisms (Landesman et al. 2005).

Ethanol has been widely used as a gasoline additive worldwide. The production of ethanol fuel has been

Fig. 4 Schematic for production of bioethanol from lignocellulosic duckweed feedstock



increasing over the last 10 years and reached a level of 85.2 billion liters in the year 2012 (Renewable Fuels Association 2013). The United States is the world's largest producer of bioethanol fuel, accounting for nearly 47% of global bioethanol production. Brazil is the world's largest exporter of bioethanol and second largest producer after the United States (Balat and Balat 2009). More than 95% of all cars sold in Brazil are 'flex-fuel' cars that can use any blend of gasoline and ethanol (Amorim et al. 2011). Using ethanol-blended fuel for automobiles can significantly and safely reduces petroleum use and greenhouse gas emissions (Wang 1999; Uhler et al. 2001). These carbohydrates are broken down into simple sugars by combination reactions. The alcohol is typically in a concentration of around 8–10% before distillation removes the water to a purity of 95–96%. Wastes from ethanol production such as distillers dried grain soluble (DDGS) are obtained as co-products. DDGS have many possible applications depending on the chemical characteristics of the DDGS but are commonly used to produce electricity or burned for heat (Landesman et al. 2005). Their byproducts could provide additional benefits besides biofuels (Nahar and Sunny 2016). Duckweed culture in wastewater treatment plants offers dual benefits of low-cost nutrient removal and biofuel production, and as such, are superior to other biomass with regard to the cost and ease of harvesting.

It is evident that lignocellulosic biomass is of great potential importance for ethanol production because the material is abundant in many regions of the world. However, conversion of lignocellulosic biomass to bioethanol is difficult and prohibitively expensive because of the tight structure of the biomass (Sarkar et al. 2012). Among the three platforms for bioethanol production, the starch platform is currently the most widely used because of availability of the feedstock and relatively mature technology. However, since almost all the current starch feedstocks (corn, rice, wheat, sweet potatoes, etc.) are important food and feed sources needing precious cropland to produce, there is great interest in exploring novel starch crops like duckweed that do not compete for croplands to make bioethanol production more sustainable.

As a result, besides bioethanol, biogas could be another important duckweed-based bioenergy product, which is usually produced through anaerobic digestion of organic waste materials, such as municipal organic wastes or wastewater and sludge, including agricultural waste or organic industrial wastes (Cheng 2010). Organic biomass materials usually contain mainly large-molecule compounds, such as carbohydrates, proteins, lipids and celluloses which are hydrolyzed with anaerobic bacteria to smaller molecules, such as sugars, fatty acids, amino acids and peptides. Additionally, a small amount of acetic acid, hydrogen and carbon dioxide is formed in hydrolysis. The sugars, fatty acids, amino acids and peptides are fermented by the anaerobic bacteria to volatile fatty acids (VFAs) during acidogenesis. The volatile fatty acids are completely degraded into acetic acid, hydrogen and carbon dioxide during acetogenesis. The whole anaerobic digestion process is complete when both hydrogen and acetic acid are converted to methane during methanogenesis (Cheng 2010). The starch content of duckweed can be substantially increased by manipulating growing conditions, such as pH, phosphate concentration and other nutrient concentration in the medium (Tasseron-De-Jong and Veldstra 1971; McLaren and Smith 1976). The growth rate of duckweed makes it ideal for bioethanol production (Cheng et al. 2002a, b; USDA-NASS 2013) and since it can also be grown in wastewaters with high nutrient concentrations, duckweed biomass production process could be additionally environmentally sustainable compared to other biomass alternatives. In fact, due to its tolerance to high nutrients and excellent nutrient uptake ability, duckweed has been extensively studied in tertiary treatment of municipal and industrial wastewaters, as well as nutrient recovery from swine wastewater (Alaerts et al. 1996; Shen et al. 2006; Xu and Shen 2011). Duckweed, as a green mat over the surface of water is a candidate to be easily harvested as shown in Fig. 5.

As a rapidly growing aquatic plant considered hard-to-control in ponds and small lakes, shows great promise and considered as a renewable energy with considerable opportunity to produce biofuel (Soda et al. 2015). Besides it is considered as a sustainable feedstock for bioaccumulation. Since it can grow in any type of waterbody, it can convert high nitrogen and high phosphorus water into much cleaner

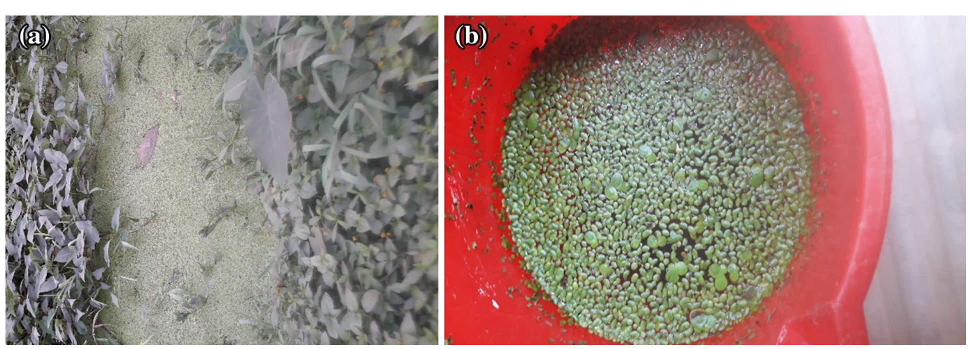


Fig. 5 **a** Duckweed cultivation and collected samples from the surface water (sampling site) from North South University (NSU) premises, and **b** at NSU laboratory four days after collection

water and at the same time massively increase in biomass in short amount of time with high content of starch. For producing biofuel, a few processes exist for duckweed refineries that use proven existing technologies to produce gasoline, diesel and kerosene. Those technologies include conversion of biomass to a gas; conversion of the gas to methanol, or wood alcohol; and conversion of methanol to gasoline and other fuels (Baliban et al. 2013). Duckweed refineries could produce cost-competitive fuel by thermochemical conversion of biomass into gasoline, diesel for transportation sectors and even jet or aviation fuel for use in air transportation (Baliban et al. 2013).

Potential for phytoremediation in wastewater treatment

Phytoremediation is a low cost, solar energy driven cleanup technique for water. It is the direct use of living plants for in situ, or in place, removal, degradation, or containment of contaminants in water and soil. Phytoremediation is thus basically a cost-effective, plant-based approach of remediation of wastewater that takes advantage of the ability of plants to concentrate elements and compounds from the environment and to metabolize various molecules in their tissues. It refers to the natural ability of certain plants called hyper accumulators to bio accumulate, degrade, or render the harmless contaminants in water and soils. Over the years, duckweed-based phytoremediation has been studying experimentally in various settings (Zhao et al. 2012; Patel and Kanungo 2010; Saha et al. 2015).

Duckweeds also received considerable attention for wastewater treatment because of their rapid growth and high nutrient uptake (Cheng et al. 2002a, b; Dalu and Ndamba 2003; Mohedano et al. 2012; Ran et al. 2004; Xu and Shen 2011) and thus its potential use for phytoremediation by extracting carbon, nitrogen, phosphorus from water. With added knowledge of physiological and molecular mechanisms of phytoremediation, biological and engineering strategies can be designed to optimize and improve phytoremediation potential. In addition, several field trials confirmed the feasibility of using plants for environmental cleanup (Balat and Balat 2009). Toxic heavy metals and organic pollutants are the major targets for Phosphorus and Nitrogen removal from domestic, industrial, and agricultural wastewaters is. Duckweeds especially have thin and long root systems used in water purification system (Fig. 6, Nahar, Sunny 2019, unpublished data, 20 days old plant) and the phytoremediation properties grow as the plants grow to maturity. Figure 6 shows growth of roots of the Duckweed Lemna strain.

Duckweed is also considered as promising agents for nutrient removal from wastewater effluent (Toyama et al. 2018). Due to their rapid nutrient uptake and strong

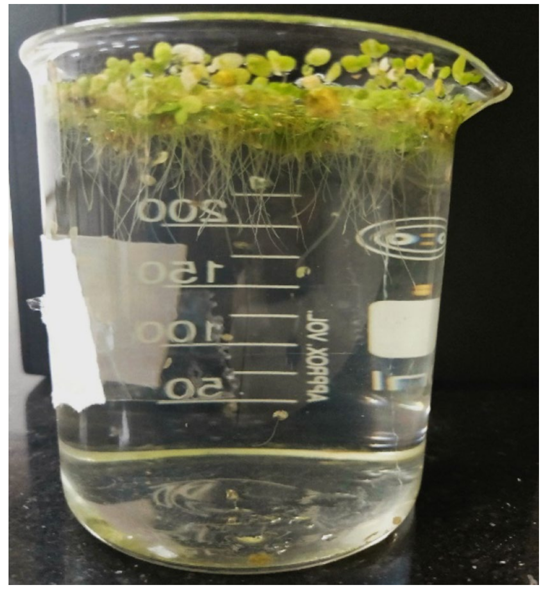


Fig. 6 Duckweed with root systems at the laboratory of the Department of Environmental Science and Management, North South University, Dhaka, Bangladesh

potential as a renewable bio resource, the mentioned aquatic plants have been highlighted as promising tools, combining energy-saving and low-cost nutrients removal, especially Nitrogen and Phosphorus (Soda et al. 2013; Zhao et al. 2014). With such bioaccumulation potential, nutrients are efficiently removed from wastewater in polyculture of duckweed, with a high starch accumulation, providing dual applications eutrophic water advanced treatment and starch accumulation (Chen et al. 2018) besides biofuel production.

In Bangladesh, duckweed technology development and integration of wastewater treatment has been first introduced by a non-governmental organization (NGO) called PRISM Bangladesh in 1989. By 1993, a full-scale system for wastewater treatment was installed at the Kumudini Hospital Complex (KHC) in Minapur, Bangladesh (Gijzen and Ikramullah 1999). In a joint cooperation between IRE and PRISM, a study was performed on the full-scale duckweed-based treatment system at KHC PRISM. Bangladesh has been continuously involved in duckweed-based wastewater treatment, both in centralized systems as well as in small-scale village settings. PRISM Bangladesh also operates a duckweed-based wastewater treatment system in Mirzapur Kumudini Hospital Complex (KHC) in Tangail with total wastewater treatment system capacity of 14 ml, where 2.4 hectares of land being used for both wastewater treatment plant and duckweed fed aquaculture (Alaerts et al. 1996).

As such, aquatic energy crops have several major advantages over terrestrial energy crops as they can take up nutrients directly from wastewater with the extensive root system, they do not need extra fertilization or irrigation. They can grow throughout the year, and do not compete with food crop production and agricultural land use, making it a superior candidate compared to existing biomass options.

Biogas production

As biofuel production experienced tremendous growth in the world in the last few years in developing countries, there has also been a great interest in biogas production from different organic feedstocks, such as animal manure, organic municipal wastes and agricultural residues (Linke 2011). Aquatic plant biomass has emerged as an alternative for the production of renewable fuels such as biogas by anaerobic digestion (AD), a process which is one of the technologies used to produce energy as well as to reduce the organic content of biomass. As duckweed grows aggressively in farm ponds, lagoons and other water bodies receiving agricultural runoff, in Bangladesh's context, it constitutes a readily available biomass source that could be easily added to farm-scale anaerobic digesters.

Duckweed has been tested as feedstock for biogas production shows higher cellulose and low lignin content indicate its potential for higher biogas production (Yadav et al. 2017). Two promising procedures like solar drying (35 °C) and the use of two-stage reactors with low-cost techniques and bio-methane yield could be improved as well as biomass harvested during wastewater treatment (Tonon et al. 2017). Methane content was observed in digesters operating around 35 °C, to produce the highest biogas yields (Ramaraj and Unpaprom 2016; Yadav et al. 2017). Additionally, duckweed's promise as a new energy source for bioenergy is due to its ability to efficiently sequester CO_2 in the environment.

Biogas by anaerobic digestion of biomass, i.e. with the absence of oxygen or air in presence of bacteria allows the bacterial decomposition to take place in three phases—Hydrolysis phase (*hydrolysate*), the acid phase (*acidogenesis*) and the methane phase (*methanogenesis*). Duckweed can be also a potential lignocellulosic feedstock when co-digested with cattle dung, a common fuel in Bangladesh. Methane content of the biogas from co-digested feedstock is comparable to the biogas from cattle dung alone (Yadav et al. 2017). There are different methods to produce biogas from biomass with methane fermentation by anaerobic digestion is the most feasible and cost-effective technology to produce biofuel from organic matter, including plant-based biomass, like duckweed (Appels et al. 2011; Chynoweth et al. 2001; Sawatdeenarunat et al. 2016). Figure 7 shows the simplified process model for biogas production from duckweed biomass. Some recent studies demonstrated methane production by anaerobic digestion of duckweed biomass (Cu et al. 2015;

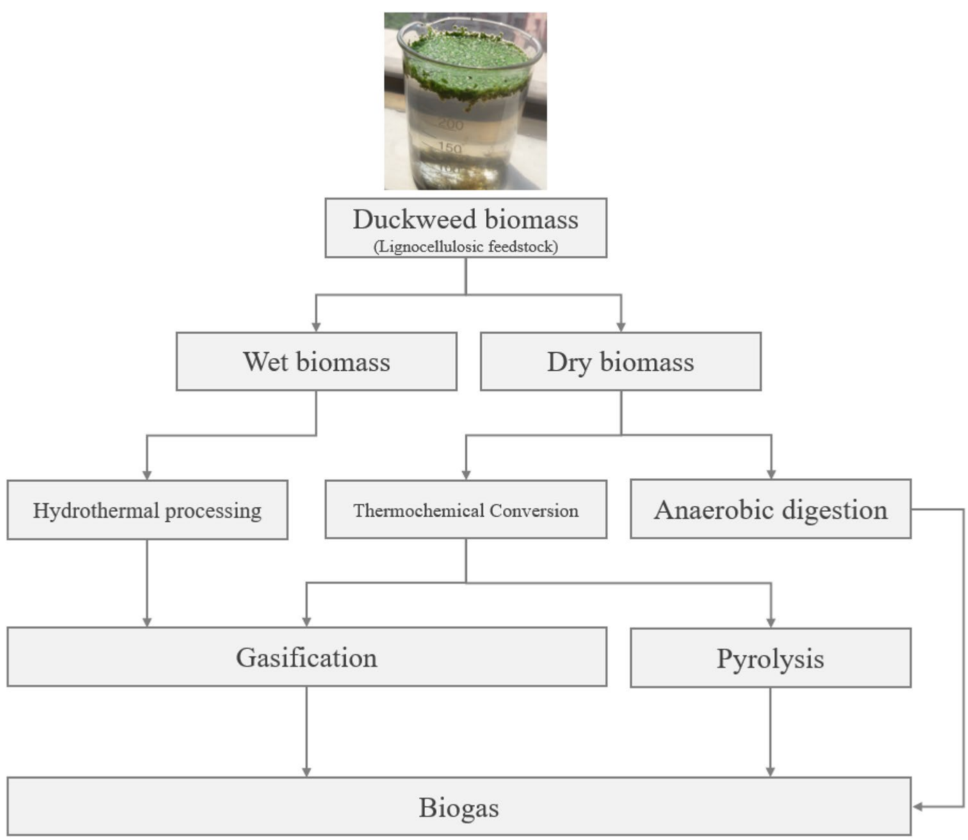


Fig. 7 Schematic of production of biogas from lignocellulosic duckweed feedstock

Gaur et al. 2017; Ramaraj and Unpaprom 2016; Yadav et al. 2017) where methane production potentials were higher than or similar to those of crops showed higher nitrogen removal and biomass production rates, and thus higher ethanol and methane production potentials.

Technology potential of biofuels given current national demands

Bangladesh has 2.17% to 15.4% of its land space as wetlands. 2% of them are lakes while the rest are rivers, freshwater wetlands, such as oxbow lakes and backswamps (locally known as *haors*, *beels*, *baors*) saltbeds, lakes and estuarian areas (Nahar et al. 2011). Considering that 7.5% of this can be appropriate candidates for duckweed cultivation due to land ownership, quality, orientation and availability, almost 1.1 million hectares can be considered the technological potential for biomass production using duckweed.

At 20–53 tons per hectare (t/ha) of duckweed biomass production each week (Iqbal 1999; Xu et al. 2012), an average yield of 35 t/ha results in annual biomass yield of 1750 t/ha or 1.94×10^9 tons for the country. Studies show that an average of 025% starch per ton of biomass can be yielded (Xu et al. 2012), resulting in approximately 800 L of ethanol per ton or 1.55×10^{12} L of ethanol annually for Bangladesh. In 2017, Bangladesh directly consumed approximate 171 petajoules (PJ), or 1.62×10^5 billion British thermal units (BTU) of liquid petroleum and petroleum-based products, and 402 petajoules or 2.8×10^5 billion BTU of natural gas. This statistic does not include natural gas or petroleum used in producing electricity (IEA 2016). In other words, if duckweed biomass could be used to produce ethanol annually (81,800 BTU per gal or 309,848 Btu per liter) at 1.55×10^{12} l, even 1% of the available wetlands would contribute to 64×10^6 billion BTU of fuel—a considerable share of currently foreign-imported fossil fuel. Alternatively, at co-digested yield of 560 ml/t of biogas each day (Yadav et al., 2017) or 85 L per ton annually (assuming 150-day year to account for lags in germination or production) at 21 Btu per liter energy content of biogas, approximately 3.5×10^{12} BTU of biogas could potentially replace fossil-fuel based natural gas for different end-use services. The downstream impacts of not exploring and flaring natural gas sites, or importing foreign oil-based products could provide further environmental benefits.

Various end-use services are rendered from these two fuel types, such as transportation (CNG and petroleum-based gasoline and diesel for motorcycles, cars, trucks, boats and irrigation pumps) but also for building uses, in residential, commercial and industrial settings. Besides a supply-side assessment of the availability of duckweed, i.e. dependent on the availability or potential production of biomass-based energy from available feedstocks, we can also conduct a demand-side assessment of potential, i.e. driven by the need for units of fuel per capita. In other words, rather than evaluating the total amount of biomass, or derived fuels, that could be produced each year, we can assess how much fuels would be needed to meet existing yearly demand of fuels within the country. One way to formalize this model is as an extension of the biofuel-based land use requirement assessment (Nahar et al. 2011).

$$\frac{1}{Cy}\frac{\alpha_{gas}}{P_T}\sum_{i=i}^{X_j}\left(\frac{Q\times R}{Q/E}\right)$$

where, we define wetland requirement as hectares per capita of fuel demand, C_y is the biofuel yield, α gas is the performance yield ration between replacement biogas and ethanol, to the replaced natural gas and petroleum-based gasoline or diesel, respectively; for P_T or the total population of a region, here the country of Bangladesh, for each X_j end use, such as the *Xth* bus, truck, car, motorcycle or boat, for *Jth* sector, i.e. transportation; or *Xth* cooking, heating and lighting, for residential or commercial buildings as the J. Q is the activity metric, per X_j, such as miles travel for transportation or square footage of home heating or lit, or meals cooked; per average fuel requirement per unit of fuel.

Conclusion

Due to the rising concentrations of greenhouse gases and the damaging impacts on the environment due to global economic dependency on fossil fuels, finding economically viable fuels from biological resources has been a key scientific target. As a riverine country, Bangladesh's geography is favorable for biofuel production from non-edible, second generation feedstocks. Researchers have tried for years to unlock a method to profitably harvest oils from aquatic biomass for energy production purposes but failed to develop a commercially feasible and environmentally sustainable solution throughout its lifecycle.

Duckweed could be considered a suitable candidate to cultivate in Bangladesh because of its climate to yield quantities of biomass. Duckweed contains rich, organic substances which are suitable to use in anaerobic digestion and fermentation process to convert biomass into biogas and ethanol. Biofuel produced from duckweed could be considered a promising aquatic source and a sustainable and alternative energy resource for future use. About 6.1 million hectares of infertile lands and water area in the country can be used for duckweed production while treating industrial wastewater around the country.

Future research needed in this area includes selection of varieties and sites, optimization of biomass production, enhancement of starch accumulation in duckweeds and use of duckweed for production of various biofuels in cost effective ways to compete with conventional oil. This includes not only selecting high-performance strains, or improving starch enrichment and conversion, but developing technologies for large-scale operations. More research is needed before widespread projects can be planned or funded as to not enable unintended consequences to manifest at different stages. Research at the intersection of selecting convenient species of duckweed and establishing economic conversion methods with focus on production cost reductions still needs to be carried out.

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