Chapter

Contribution of Anaerobic Digestion Coupled with Algal System towards Zero Waste

Lakshmi Machineni, R. Aparna Rao and Anupoju Gangagni Rao

Abstract

Global environmental protection is of immediate concern and it can only be achieved by avoiding the use of fossil fuels. In addition, waste disposal and management could be made remunerative through the generation of renewable energy so that sustainable development is ensured. India is an agriculture-based country, and paddy residues such as rice straw and rice husk are the largest agricultural wastes in India. Currently, the common practice to dispose paddy residues is through field burning, but this has adverse effects on the air quality and consequently on people's health. However, utilization of lignocellulosic and non-food agricultural residues such as paddy residue for biogas generation by solid-stated anaerobic digestion (AD) is promising and this can substitute fossil fuels. Paddy residues for biogas production via AD has not been widely adopted because of its complex cell wall structure making it resistant to digestion by microbial attack. In addition, sequestration of carbon dioxide from biogas by algal biomass cultivated in an integrated algal bioreactor could be a promising option for biogas enrichment due to its unmatched advantages. This chapter presents the overview on utilization of non-edible residues for biogas production and its enrichment via algal biomass by means of circular bioeconomy.

Keywords: biogas, non-edible residues, algae, enrichment, zero waste

1. Introduction

Agriculture is a potential sector of the global economy, and paddy production has risen nearly 4 times in the last 60 years. India is the second largest paddy producer after China in the world, making more than 10% of the global share and thereby non-edible paddy residues, namely rice straw and rice husk [1]. The farmers are burning million of tons of paddy residues that create smog that contributes to heavy pollution in India. Furthermore, it also reduces the nutrients in the crop soil and damages desired microbial populations [1]. Therefore, management of the large quantities of paddy residues is becoming a significant environmental issue. This and the global warming effect have emerged as a research interest to utilize paddy residues as a feedstock for renewable energy like biogas production. Thus, biogas generation from paddy residues can be a major step toward harnessing one of the world's most prevalent, yet fully unutilized, renewable energy resource.

Carbon dioxide (CO_2) is a key greenhouse gas mainly releases from burning of fossil fuels namely oil, coal, and lignocellulosic biomass [2–4]. Although conventional physio-chemical and thermal approaches to reduce CO_2 have their own advantages, there is an urge to focus on biological transformation of CO_2 to energy and products of interest [5, 6]. Algae use CO_2 as a carbon source during photosynthesis and release oxygen into the atmosphere [7, 8]. In parallel to CO_2 mitigation, algal biomass has applications in production of single cell protein, bioactive compounds, pigments, cosmetics, pharmaceuticals, biogas, biofertilizer, bioplastics, biohydrogen and phytoremediation [6, 9–11]. Thus, application of micro algal biorefinery concept to produce renewable energy will enhance the economics of bioenergy production by means of circular bio-economy. The current chapter focusses on overview on anaerobic digestion, different conventional methods and microalgal biorefinery for the enrichment of biogas. In addition, the last section of the chapter discusses in short about the algal biomass recovery and its potential applications by means of circular bioeconomy.

2. Anaerobic digestion of lignocellulosic biomass

Over the past decade, anaerobic digestion (AD) has been used effectively for the degradation of agricultural lignocellulosic biomass-maize straw and wheat straw-for the production of biogas, which could be used for combined heat and power (CHP) application [12–14]. Paddy residues, composed of lignocellulose, are difficult for anaerobic microorganisms to degrade as they have a complex polymeric carbohydrates that must be preprocessed into simpler monomers-called platform molecules-that can be further converted into bioenergy [15]. A number of researchers, however, have exclusively paid attention using rice straw for biogas generation through AD [14–17], but AD of pretreated paddy residues has rarely been reported.

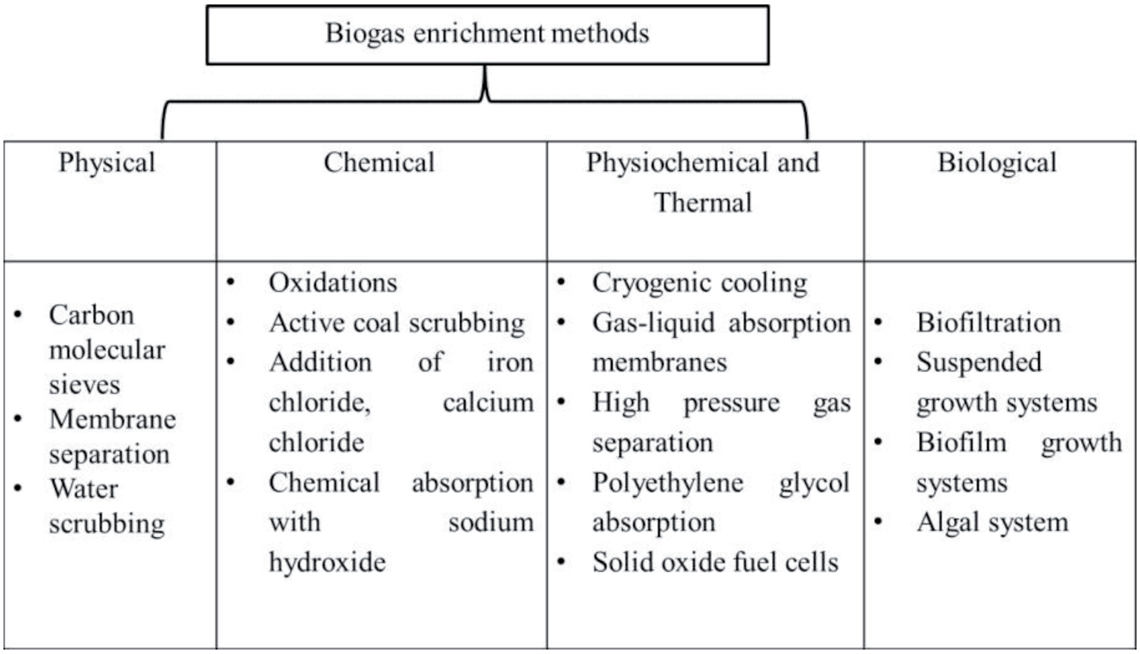
Controlled delignification and depolymerization of paddy residues into simpler monomers, called platform molecules, are rather challenging and specifically mandatory on a technical scale and this problem is yet to be solved, for the synthesis of bioenergy. A variety of pretreatment methods have been applied for lignocellulose biomass [14, 18, 19]. It is worth noting that the pretreatment step not only helps to release platform molecules for higher degradation by anaerobic consortia but also helps to remove toxic metal elements from biomass, which are not biodegradable and hence long-term accumulation in anaerobic digesters inhibits stable digestion of biomass in the long run. In addition, a number of important limitations such as characteristics of the pretreated digestate, different solid loadings and carbon-to-nitrogen (C/N) ratio to improve methane yield have to be investigated on immediate necessity base.

Several previous studies have reported that biogas produced from untreated rice straw is composed of methane (CH_4, ~50–75%), carbon dioxide (CO_2, ~25–50%), other impurities in small quantities such as water (H_2O, ~5–10%), hydrogen sulfide (H_2S, ~0.005–2%), siloxanes (0–0.02%), oxygen (O_2, ~0–1%) and nitrogen (0–2%) [20–23]. Biogas is enriched by removing unwanted gases (CO_2, H_2S and water vapor) to increase the calorific value, so that it is economical to compress and transport to longer places for distribution or move to other area for multifaceted applications [24–26]. Biogas production by AD is an established technology that allows farmers to generate more income from biomass waste and closing nutrient cycles [25, 27]. These synergies can be extended even further if microalgal cultivation is added to produce algae-based bioproducts. Products from microalgae, such as feed and feed additives, can again be used in the agricultural sector, which closes material cycles and extends the value chain for the biogas operator. Moreover, algae offer potential alternatives for multifaceted applications because of their high protein content and biomass yield, ability to be cultivate in their natural environment and zero effect on the food chain.

3. Biogas enrichment

Removal of CO_2 increases the percentage of biomethane in biogas. The processes involving CO_2 capture and storage are gaining attention as an alternative for reducing CO_2 concentration in the enrichment of biogas [22, 28, 29]. Several physiochemical [22, 30–32], biological [33, 34] and thermal methods [29, 35] for biogas enrichment process or purification of biogas have been reported [20, 29] (**Table 1**). For example, purification of biogas using calcium hydroxide ($Ca(OH)_2$) solution, thus CO_2 would be reacted with $Ca(OH)_2$ solution to form the precipitate of calcium carbonate ($CaCO_3$) has been reported [36]. Potential adsorbents such as activated carbon, silica gel, clay, alumina and zeolite have been reported for gas purification [37–40].

Although every adsorbent system and conventional methods have their own advantages, these technologies are considered as expensive and environmentally hazardous short-term solutions, as there are still concerns about the environmental sustainability of these processes. Alternatively, microalgal sequestration of CO_2 and its transformation to value-added biomass could be a potential solution due to its feasible and unmatched advantages over current approaches [40–42]. The waste product at the end of algal CO_2 sequestration is oxygen, clean air. Microalgae will utilize inorganic carbon from CO_2 into lipids under sunlight and increase the accumulation of biomass and algal oil [42]. As photosynthesis is a key process for microalgae metabolism and their growth, these systems are suitable even for regions with high temperatures and sunlight exposure. The effectiveness of CO_2 mitigation and its consumption by algae can modify according to the state of the algal physiology, gas residence times, light intensity, nutrient availability



Biogas enrichment methods

Physical	Chemical	Physiochemical and Thermal	Biological
• Carbon molecular sieves • Membrane separation • Water scrubbing	• Oxidations • Active coal scrubbing • Addition of iron chloride, calcium chloride • Chemical absorption with sodium hydroxide	• Cryogenic cooling • Gas-liquid absorption membranes • High pressure gas separation • Polyethylene glycol absorption • Solid oxide fuel cells	• Biofiltration • Suspended growth systems • Biofilm growth systems • Algal system

Table 1.
Different methodologies for biogas purification.

and temperature. It has been reported that CO_2 sequestration as high as 99% is attainable upon defined environmental and nutritional conditions, and with gas residence times as low as two seconds [42–45]. In addition, microalgal system combined with AD systems and the synergy between algae-bacteria can help to avoid the power demands from aeration, which actually represent almost 60% of the total energy requirement of waste effluent treatment plants in industries. During photosynthesis, algal system provides oxygen that is necessary for aerobic microbes to digest and biodegrade organic effluents, consuming in turn the CO_2 released due to bacterial growth [44].

4. Microalgae

Microalgae are phototrophic microorganisms that generate biomass with simple nutritional and low light energy and CO_2 requests. These are photosynthetically highly efficient (~10–20%) in comparison with terrestrial plants (1–2%) to fix CO_2. It was reported that more than 100,000 species exist. Advantages of being sustainable at high flue gas concentration and cogeneration of top-value products put these as the preferential and potential organisms (**Figure 1**). Microalgae have the ability to synthesize high amounts of proteins nearly 51–71% of dry matter compared to meat, 43%, soybeans 37%, milk 26% and rice 8%, which are essential for use in human and animal food supplements. Not only proteins, microalgae carbohydrates, ~25% of its dry matter, are made in the forms of simple mono- and polysaccharides, which are easy to digest. Algae are the best candidates for the production of biodiesel as they do not compete with edible crops and can produce up to 80,000 L of oil per acre per year, which is almost 31 times higher than biodiesel produced by the best terrestrial crop, namely palm tree. Moreover, biomass harvested and dewatered from microalgae belongs to the groups of *Spirulina*, *Chlorella*, *Dunaliella*, *Nostoc*

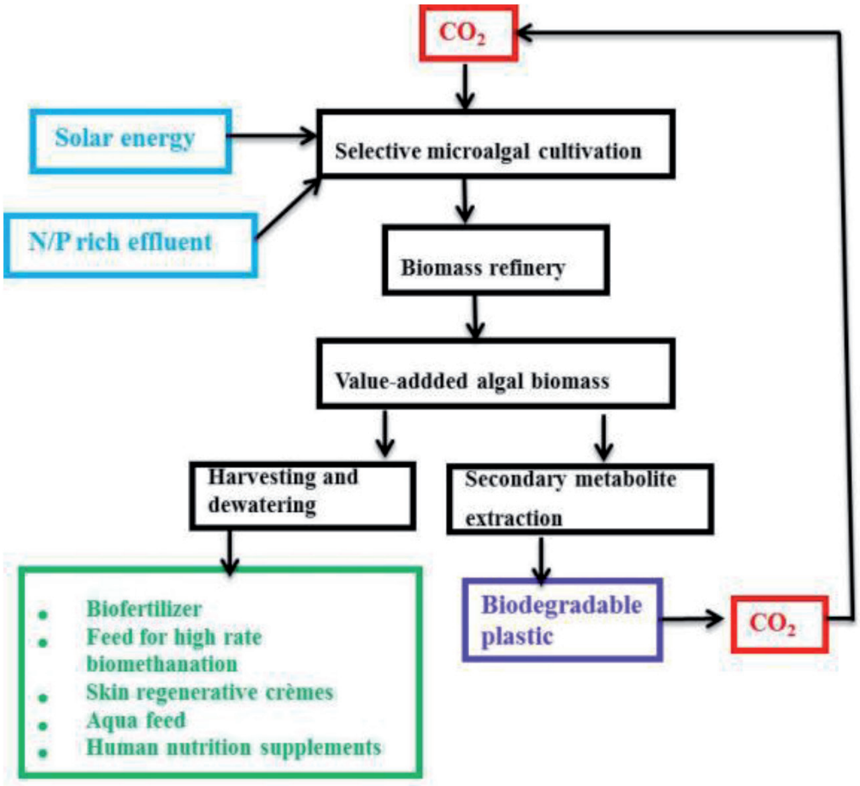


Figure 1.
Schematic algal biorefinery showing different products that can be obtained from microalgal biomass.

and *Aphanizomenon* and is available in human healthy foods industry in the form of powders, capsules, tablets, pastilles and liquids [46–48].

Some algae can increase their biomass with double growth rate within 3.5 h in their exponential phase. Algae growth yield is three to four times higher in the presence of soluble gases, namely CO_2 and H_2S [49, 50]. As the biogas passes through algal reactor, methane, which is not soluble, flashes off, whereas CO_2 and H_2S essentially infuse and completely dissolve in liquid stream. By allowing biogas stream which is typically composed of 60% methane, 39% CO_2 and less than 1% H_2S passes through coupled algal reactor, will transform to a biogas that is over 90% methane and the CO_2 and H_2S being reduced by 85–95% by algae biomass [49, 50].

Biomass cultivated in photobioreactors can be utilized for several applications, including substrate for bioenergy such as biogas, biofuels, biofertilizers, biosorbents and biopolymers [50, 51]. For instance, biopolymers recovered from algae can be adapted into packaging materials and have the advantage of being renewable [52].

What really makes the use of algae a thriving technology is that these microorganisms have the potential to efficiently remove nutrients from wastewater and provide high-value biomass energy with low cost. Enclosed bioreactors and open ponds are the two predominant methods for microalgal cultivation (**Figure 2**) [53]. Interestingly, closed photoreactors provide sterility and allow for much greater control over culture parameters such as light intensity, CO_2, nutrient levels and temperature, and thus higher biomass productivities can be reached [11]. In parallel to CO_2 mitigation, algal biomass has applications in human nutritional supplements such as vitamins, Omega-3 fatty acids, biotin, production of antiaging creams, antiirritant creams, skin regenerate creams, biogas, biofertilizer, aqua and animal feed, and treatment of waste water [46].

Recently algae-based strategies for the removal of toxic minerals such as arsenic (As), bismuth (Bi), bromium (Br), cadmium (Cd), chromium (Cr), mercury (Hg) and lead (Pb) have also been reported individually or in a mixture, and some commercial applications have been initiated [54–56]. Therefore, a sustainable closed loop microalgae-mediated CO_2 sequestration system could be integrated with biogas generation infrastructure after optimization of algal cultivation system and

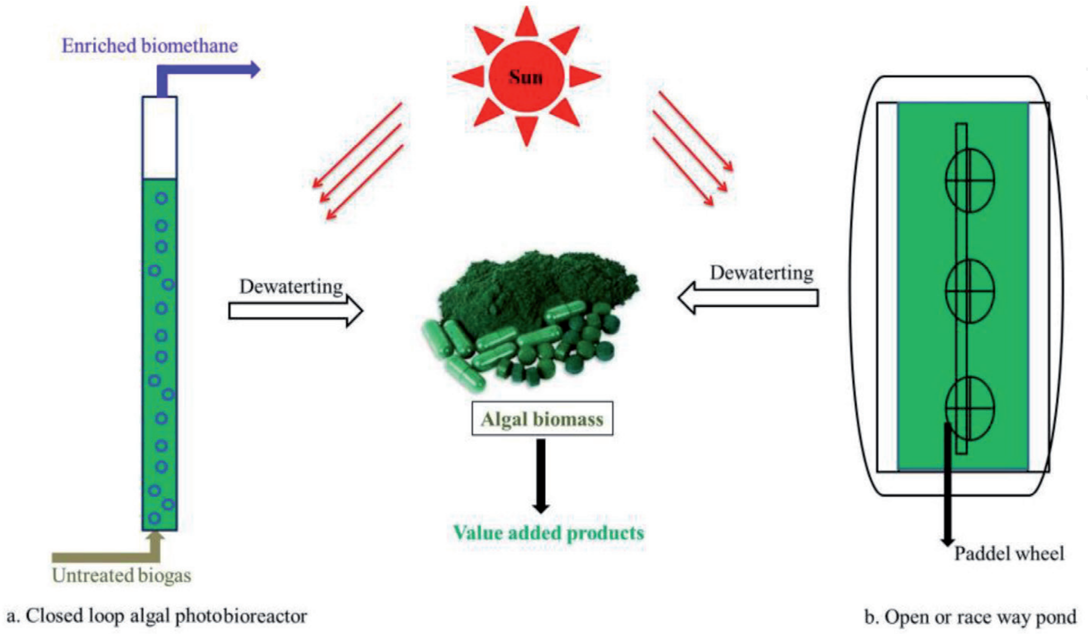


Figure 2.
Two different methods of microalgal cultivation.

key process parameters, and recovery of novel bioproducts from harvested microalgal biomass.

5. Biomass harvesting and dewatering

Development of biorefinery for production and conversion of algal biomass will be the unified solution to meet the day-by-day increasing energy demand and to reduce risks associated with global warming due to tailpipe emissions. The microalgal-based production chain is classified into three series of steps, namely biomass inoculation and cultivation, harvesting and dewatering, and extraction of concentrated biomass for desired applications. The systems for algal cultivation can be tanks, trays, open ponds, closed or hybrid photobioreactors. It has been suggested that these systems deliver a very dilute biomass concentration ranging from 0.05 to 0.075% dry matter for open pond systems and 0.3–0.4% for closed reactors [57]. Hence, there is an immediate requirement to develop an efficient algal dewatering process to reach the biomass up to 30% in total dry product. Concentrating algal biomass and purifying it into products from broth occur in two stages: a single step of harvesting followed by one- or two-step separate biomass dewatering, which is then fractionated and extracted to extend the "shelf-life of biomass" and to make the product accessible for further application [58, 59].

Recent advance and novel high-tech research in bioprospecting new strains, breakthrough innovations in culture cultivations and complete process optimization are certainly increasing our hope about the forthcoming achievements by microalgal biorefinery. However, the potential of successful commercial deployment is associated with simple and indigenous innovations in downstream operations, specifically cell harvesting, cell disruption and extraction, which can actually cut down the costs at a biorefinery level, along with process integration. During algal biomass cultivation, the harvesting process is the main constraint, representing more than 20% of the total production cost due to low biomass density ($0.2–2\ g\ L^{-1}$) and small size (10–30 μm). The methods for harvesting either used independently or in combination. However, most of these methods still involve economic or technological drawbacks, such as a high-energy cost (centrifugation), algal biomass contamination (chemical flocculation), or nonfeasibility of scaling-up. Besides the operational cost, concerning selection of the adequate harvesting method, several aspects such as the following should be considered: (i) harvesting speed, (ii) harvesting efficiency, and (iii) density and quality of biomass in the resultant concentrate [60, 61]. Among different polymers, the chitosan prepared from the waste of white shrimp is reported as a good cost-effective and efficient flocculant for algal biomass because of its properties such as faster deposition rate [57]. However, the optimal pH, chitosan dosage, chitosan physiochemical characteristics and flocculation time to achieve ~100% of algal biomass harvesting efficiency and optimization of storage condition for harvested biomass should be investigated more clearly for further applications.

Because of high protein content and biomass yield, microalgal biomass offers a potential alternative for bioplastic and biofertilizer production, either directly or in secondary metabolites form. Dewatered algal biomass can be modified into bioplastic and biofertilizer. Bio-based plastics help to "decarbonise" the economy. However, unlike soy protein isolate or feather meal protein, it is not economical or technically feasible to extract the protein from the algal biomass [11]. Consequently, more research must be developed aiming to optimize the extraction of secondary metabolites to create a sustainable and biodegradable alternative to fossil fuel–based plastics. After secondary metabolite extraction, the residual algal biomass can be reused as feed for biogas production via anaerobic digestion and biofertilizer. Several researchers have developed an indigenous assembly of macroalgae, which was installed and grown in CO_2- infused wastewater effluent (**Figure 2**) [62–64]. Later, algal biomass was harvested and co-digested with sewage sludge to enhance bio-methane production. Several techno-economic constraints have to be solved for the generation of biomethane from algal biomass is economically feasible [63, 65]. For instance, potential issues to be focussed further to enhance biomass conversion to biomethane are high sensitivity of methanogenic microorganisms, unbalanced C/N ratio of algal biomass, and high lipid contents, and cost associated with biomass recovery [65].

In addition to different solutions to huge environmental problems like deficiency of nitrogen content in the soil composting causing pollution must work in parallel with other action. Algae can serve the purpose by fixing atmospheric nitrogen and synthesizing plant growth promoters as nitrogen content of the soil is the second major factor affecting plant growth after water [66, 67]. Biofertilizers made from algae will be an effective replacement for chemical fertilizers by means of circular bioeconomy. Thus, the application of microalgal biorefinery concept to produce renewable energy will enhance the economics of bioenergy production by means of circular bioeconomy.

6. Conclusions

Lignocellulosic biomass has a huge potential for biogas production, which would be a sustainable alternative for nonrenewable fossil fuels. Upon optimization of lignocellulosic biomass delignification, high rate of biomethanation would be a possible feasible solution to fill previous research gaps without using costly fermentable sugars from food sources. Most importantly, having a clearer understanding on biomass characteristics before and after pretreatment will provide information about storage of delignified feedstock, which is key point for saving renewable biomass in order to meet energy demand of future generation before it gets exploited like fossil fuels. Later, presenting the CO_2 biocapture by selective algal strain could reduce cost associated with conventional chemical CO_2 scrubbing technologies and could be a breakthrough with potential applications. In addition, algal flocculant chitosan can be extracted from shrimp waste, which will be cost-effective for harvesting and dewatering of algal biomass by means of circular bioeconomy. It is most important to achieve ~100% harvesting of microalgal biomass with chitosan under optimal physiochemical parameters associated with flocculation approach. Polysaccharides and oils recovered from dewatered algae can adapt as lightweight, waterproof biodegradable plastic material, and organic fertilizer to enrich crop yield. However, more research on anaerobic digestion of lignocellulosic biomass coupled with algal systems could be useful to commercialize biogas production from widely produced low-cost substrate, and cultivation of algae in parallel for CO_2 mitigation results in top-value chemical generation with home-grown technology.

Author details

Lakshmi Machineni[1,2]*, R. Aparna Rao[2] and Anupoju Gangagni Rao[2]

1 CSIR-IICT, Hyderabad, India

2 Bioengineering and Environmental Sciences (BEES) Group, Department of Energy and Environmental Engineering (DEEE), CSIR-Indian Institute of Chemical Technology (IICT), Hyderabad, Telangana State, India

*Address all correspondence to: machineni.402@csiriict.in

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