



Towards sustainable agriculture with carbon sequestration, and greenhouse gas mitigation using algal biochar

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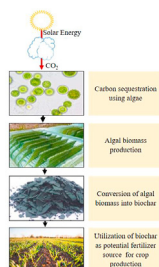
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HIGHLIGHTS

- Overall, nutrient value of algal biochar is discussed in this study.
- The effect of algal biochar on soil health improvement agriculture soil is discussed.
- Greenhouse gases mitigation through biochar is reviewed.
- Algal biochar potential as fertilizer are also proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

With the increase in the world's population, demand for food and other products is continuously rising. This has put a lot of pressure on the agricultural sector. To fulfill these demands, the utilization of chemical fertilizers and pesticides has also increased. Consequently, to overcome the adverse effects of agrochemicals on our environment and health, there has been a shift towards organic fertilizers or other substitutes, which are ecofriendly and help to maintain a sustainable environment. Microalgae have a very high potential of carbon dioxide (CO₂) capturing and thus, help in mitigating the greenhouse effect. It is the most productive biological system for generating biomass. The high growth rate and higher photosynthetic efficiency of the algal species compared to the terrestrial plants make them a wonderful alternative towards a sustainable environment. Moreover, they could be cultivated in photobioreactors or open ponds, which in turn reduce the demand for arable land. Biochar derived from algae is high in nutrients and exhibits the property of ion exchange. Therefore, it can be utilized for sustainable agriculture by partial substituting the chemical fertilizers that degrade the fertility of the soil in the long run. This review provides a detailed insight on the properties of algal biochar as a potential fertilizer for sustainable agriculture. Application of algal biochar in bio-refinery and its economic aspects, challenges faced and future perspective are also discussed in this study.

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1. Introduction

Pollution has been a major concern of the world for the past few decades. It has gained a lot of attention of the research world to help people around the globe for getting a sustainable environment to live within. Surface runoff from agriculture consisting of chemical fertilizers and pesticides is polluting our soil, air and water bodies, which are affecting the life badly (Pavlidis and Tsihrintzis, 2018; Kumar et al., 2019). Total fertilizer production in India has increased from 201.6 thousand tonnes in 1951–1952 to 41, 556.5 thousand tonnes in 2017–18 and the consumption has increased from 70 thousand tonnes in 1950–51 to 26,593.4 thousand tonnes in 2017–18 (FAI, 2018). According to a statistical approximation, the population of the world may cross 9.8 billion by the year 2050 (UN, 2017) with India expecting to surpass China in around 2024 (UN, 2017). This puts a lot of pressure on the agricultural sector to meet the increasing demands of food and livelihood, which in turn directly puts pressure on agricultural activities. Consequently, to fulfill the agricultural needs, chemical fertilizer consumption is likely to be increased. In this regard, it should be mentioned that chemical fertilizer production requires natural gas, coal, gasoline, etc. energies which contributes to CO₂ emission leading to the greenhouse effect and global warming as shown in Fig. 1 (West and Marland, 2002). The energy requirement for the production of N, P and K chemical fertilizers has been reported to be 55.48 GJ Mg⁻¹, 4.52 GJ Mg⁻¹ and 4.80 GJ Mg⁻¹, respectively from various sources such as coal, electricity, natural gas, gasoline, distilled fuel and post production energy requirements (for packaging, transportation and field applications) have been reported to be 57.46 GJ Mg⁻¹,

7.03 GJ Mg⁻¹ and 6.85 GJ Mg⁻¹, respectively (West and Marland, 2002). The total CO₂ emission from distillate fuel is 21.95 kg C GJ⁻¹, from natural gas is 14.54 kg C GJ⁻¹, from liquified petroleum gas is 18.69 kg C GJ⁻¹ and from coal is 25.16 kg C GJ⁻¹ (West and Marland, 2002). Further, the application of chemical fertilizers to the soil disturbs the natural nitrogen related processes, thus, in turn leading to N₂O emission and soil acidification etc. (Gao et al., 2015). Moreover, these add up to the atmospheric N₂O content, which in turn contributes to the destruction of stratospheric ozone layer (Davidson, 2009). Additionally, fertilizers contain trace elements along with the principal elements, which get accumulated in the soil system on repeated applications. These trace elements also get accumulated in the crops affecting human health adversely and become a part of the food chain (Jiao et al., 2012). For example, chemical fertilizers having phosphate are manufactured from the phosphate rock, which has a huge range of naturally occurring trace metals such as arsenic, cadmium and lead, which become a part of the NPK blends containing mono ammonium phosphate, di-ammonium phosphate and triple superphosphate. The concentration varies from nil to 21, 130 and 43 mg kg⁻¹ for As, Cd and Pb, respectively in rock phosphates around the world (Jiao et al., 2012). Moreover, chemical N fertilizers are known to affect soil microbial community composition, soil pH, mobilization and leaching capabilities of different ions (Geisseler and Scow, 2014). More than 80% of the studies reported that soil microbial composition is sensitive to NPK fertilizers (Geisseler and Scow, 2014). Introduction of chemical N fertilizer reduced microbial biomass by 15% in 82 field studies (Treseder, 2008). Similarly, in another 57 studies, microbial biomass reduced by 20% due to nitrogen addition (Liu and Greaver, 2010). Further, soil pH decreased by 0.45–2.20 units due to NPK fertilization over a period of 8–25 year in 10 field sites in China (Guo et al., 2010).

With respect to the present background, it may be considered that increasing population and food demands have exerted tremendous pressure on agriculture, thus, increasing the never-ending need for different types of soil amendments to achieve greater yields and maintain soil fertility. Since chemical fertilizers are not environmentally sustainable, other soil and environment friendly options are needed so as to maintain the nutrient balance in the soil and enhance productivity. Cayuela et al. (2014) have reported a 54% reduction in N₂O emission with biochar amended soil. Biochar is one of the most effective ways of soil amendment when compared with other strategies such as biological nitrogen fixation, synthetic nitrification inhibitors. Biological nitrogen fixation shows the problem of ammonia volatilization while urease inhibitor is effective only for 7–14 days. On the other hand, biochar can prevent nitrogen leaching, can retain excessive nitrogen and thus, reduces N₂O emission. Also, the retained nitrogen is released from biochar gradually when soil nitrogen goes deficient to support plant growth (Li and Chen, 2019).

Microalga has drawn the attention as an alternative approach for a cost effective, and ecofriendly renewable source and helpful in creating a pollution free environment (Mona et al., 2013, 2015). When compared to terrestrial plants, microalga possess higher ability to rapidly increase in biomass (Mona et al., 2011; Cheah et al., 2015). Microalgae have the potential to be used as biofuels like biodiesel, biohydrogen, biogas, produce biolipids and other valuable biorefinery products such as nutraceuticals, cosmeceuticals, pharmaceuticals, biofertilizers and also act as bioremediating agent in addition to carbon (C) sequestration (Mona et al., 2011; Wang et al., 2013; Smith and Ross, 2016; Sharma et al., 2020). They are easily cultured in open ponds or photobioreactors under controlled and optimized conditions (Yu et al., 2018). They have a huge potential for C sequestration, which is further helpful in

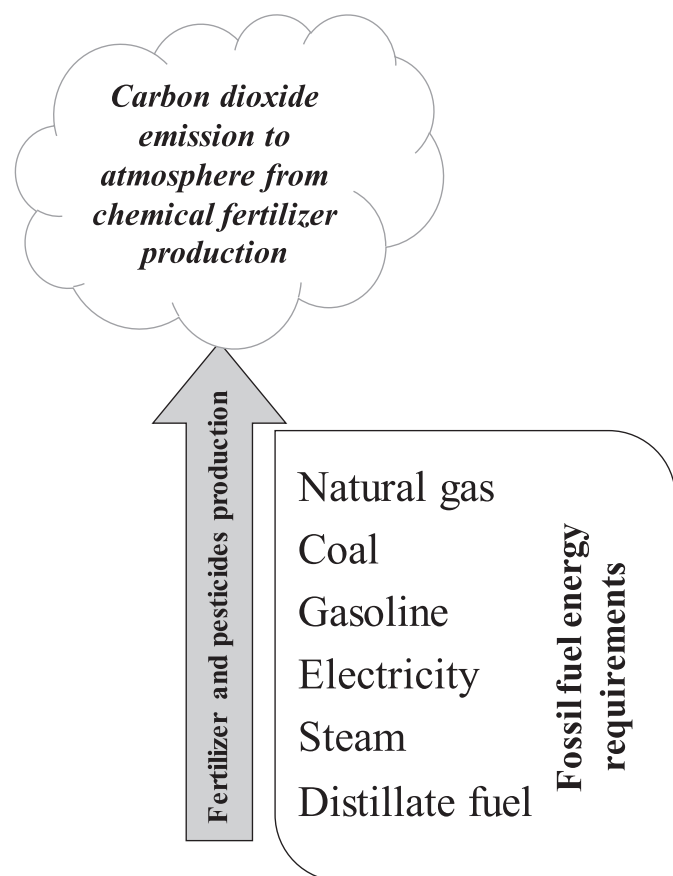


Fig. 1. Fossil fuels used in generation of chemical fertilizers cause emission of carbon dioxide.

reducing the greenhouse effect, global warming and change in climate (Cheah et al., 2015). Microalgal biomass can be transformed into biochar mostly through standard thermochemical conversion methods such as pyrolysis, torrefaction and hydrothermal carbonization. Microalgal biochar possess the potential to increase the soil nutrient content and thus, helps to increase crop productivity along with C sequestration (Yu et al., 2017a). Extensive studies have been done on biochar from different feedstocks and their properties on plant growth and agricultural improvement while biochar from the algal feedstock and its property as potential fertilizer is still in the budding stage (Bird et al., 2012). The availability of information on this topic is also limited and this has caught the author's attention as it is a budding area of science and there is more scope to learn.

In the present review article, the authors have tried to compile all the available information on algal biochar and its practical use as a nutrient source and a soil amendment method for improving the agricultural yield. It also highlights various methods for the production of algal biochar and its properties, which should be focused on for further use. The article will help the readers to get compiled information about algal biochar manufacturing, properties and its potential to be used as an agricultural amendment. Algal biomass is well studied as a biofertilizer and there is more information available in this area but not on algal biochar as fertilizer. Hopefully, this article will be the first review, which compiles detailed information on algal biochar and its utilization as a potential fertilizer.

2. Classifications and algal biomass production

2.1. Classification

Classification can be of very great help when assessing different potentials of a species. Several scientists have tried to fit algae into different kingdoms and no satisfactory attempt has been achieved yet. Several different classifications of algae are in use (Heimann and Huerlimann, 2015). NCBI contains very few genome sequences of algae and this poses a limitation on further algal studies (Higgins et al., 2015). Algae have a complicated evolutionary history and are widespread among different taxonomic groups.

Algae are polyphyletic in origin. They have been classified on the basis of photosynthetic pigments but currently, cytological and morphological characters are being taken into account (Levasseur et al., 2020). A majority of the present algae falls under the Eukaryota domain whereas only one representative, cyanobacteria falls under the Prokaryota domain of the seven-kingdom classification (Levasseur et al., 2020). Endosymbiosis of cyanobacteria has led to the present-day plastids in land plants (Viridiplanta), red algae (Rhodophyta) and a small group Glaucophyta (Heimann and Huerlimann, 2015). Lee (2018) has described algae on the basis of the chloroplast membrane enveloped by single or double membrane chloroplast endoplasmic reticulum into several groups i.e. Cyanophyta, Glaucophyta, Rhodophyta, Euglenophyta, Dinophyta, Cryptophyta, Heterokontophyta, Prymnesiophyta. The term algae consist of a diverse group of micro and macroscopic photosynthetic organisms (Lee, 2018). The group consists of unicellular organisms, some of them are multicellular forms containing chlorophyll as the primary photosynthetic pigment along with chlorophyll *b*, *c* and *d* and lack a sterile layer around the reproductive cells. They mostly occur in water (freshwater, marine and brackish water) but have diverse habitats ranging from the snowfield rocks to desert sands (Lee, 2018), some unusual places such as the fur of polar bears and sloths (Singh and Saxena, 2015) and various harsh environments such as biotic crusts in hot deserts (Lewis and Flechtner, 2002), hot springs and Antarctic snow (Broady, 1996). They occur individually or in groups or in a symbiotic association such as lichens. Algae contain lipid bodies, which are generated through photosynthesis

and can be used as a source of energy. They also possess a nucleus and the other cell organelles such as endoplasmic reticulum, golgi apparatus, mitochondria, vacuole etc. (Singh and Saxena, 2015).

They use carbon dioxide as a source of carbon and fix it through the Calvin cycle where ribulose 1, 5-bisphosphate (RUBP) is converted into 3-phosphoglyceric acid (3-PGA). They have better photon conversion efficiency than the terrestrial plants and get increased in biomass (Singh and Saxena, 2015). In this process, carbon is sequestered and gets recycled from the atmosphere into the biomass. Therefore, it can be used as a CO₂ mitigation approach and helps to combat the greenhouse gas and global warming problems. The benefit of using algae for CO₂ sequestration is that it does not require further disposal of carbon and it can be used to obtain various biorefinery products such as carrageenan, agar, β-carotene, biodiesel, biohydrogen etc. (Mondal et al., 2017).

2.2. Algal biomass cultivation and processing

The cultivation of algae negates the requirement of land as in case of the terrestrial plant-based economy. For gasoline annual requirement, microalgal production footprint is 121000 ha of the area of an open pond and 58 thousand hectares area of photobioreactors (Show et al., 2019). For microalgal cultivation and final extraction of biochemicals, various steps are performed in series i.e., cultivation, harvesting and extraction (Rizwana et al., 2018).

Open ponds and closed photobioreactors (PBRs) are usually used to cultivate algae, where PBRs are highly controlled and hybrid system (Okoro et al., 2019). The choice of the system is based on cost and reliability (Mondal et al., 2017). Capital cost investment is the most influential factor for PBR design but effective growth conditions particular to each species and efficient construction along with the material selection, size and mode of operation are crucial for cost reduction, scaling up and high biomass yield (Okoro et al., 2019). In PBRs, the growth and development of the algal biomass depend heavily on various biotic (microalgal strain, microalgal cell history and presence of other strains in the culture), abiotic (temperature, pH, light, carbon dioxide concentration, concentration of nutrients, salinity, cultivation medium and presence of toxic chemicals in culture) and process related factors (biomass concentration, the intensity of mixing and frequency of algal harvesting) etc (Okoro et al., 2019). For cultivation, species selection is a very basic step. Species should be tolerant to various environmental conditions (Rizwana et al., 2018). The hybrid system combines both open and closed cultivation systems and it is a two-stage cultivation process. The first stage of the cultivation involves photobioreactor for optimum algal mass growth and checks contamination. In the second stage, lipid production is enhanced through nutrient deprivation for algal growth (Lee et al., 2020).

After cultivation, a suitable method of harvesting is needed. This includes concentrating the algal biomass or its separation from the medium (Show et al., 2019). This contributes up to 20–30% of the total production and downstream processing costs (Barros et al., 2015; Tan et al., 2020).

Various harvesting approaches include centrifugation, sedimentation, filtration, ultrafiltration and additional flocculation, floatation etc (Yu et al., 2017a; Tan et al., 2020). The product quality and moisture content in the final product determine the harvesting method. Dehydration is performed to increase the shelf life of the extracellular polymers of bacteria and fungi (Okoro et al., 2019). A combination of two or more processes is performed in some cases to improve harvesting efficiency (Tan et al., 2020). The type of algae is the major determinant factor for choosing harvesting technology (Show et al., 2019). The harvesting of macroalgae is simpler as compared to microalgae. Macroalgae are harvested manually or mechanically through moving boats, mesh conveyors or dredgers

and then, preserved in formaldehyde and sun dried in less than 24 h to reduce moisture according to the storage purpose. Microalgae are harvested based on their density, cell charge, size and the desired product. It can be subjected to physical (flotation, centrifugation, filtration, gravitational and sedimentation), chemical (autoflocculation, inorganic coagulation, chemical coagulation and bioflocculation) or electrical assisted treatment (electro flotation, electro flocculation and electrophoresis) as mentioned by Lee et al. (2014).

After the harvesting step, biomass is subjected to the final extraction step for the desired product. It is a highly specific process. Biomass productivity generally depends on a range of factors including temperature, pH, light intensity, CO₂ concentration, algal strain, substrate mixing rate, nutrients etc (Yu et al., 2017a).

3. Algal biochar production and properties

Biomass produced can be subjected to various biorefinery approaches as depicted in Fig. 2 and the leftover biomass after extraction of the desired products can be used to produce biochar, which further can be utilized for various applications like adsorbent to treat wastewater and recover resources from it, soil ameliorant and coal as energy carrier. The picture sums up the basic steps from feedstock selection of the biomass to biochar utilization. Nautiyal et al. (2016) studied biodiesel production from *Spirulina platensis*

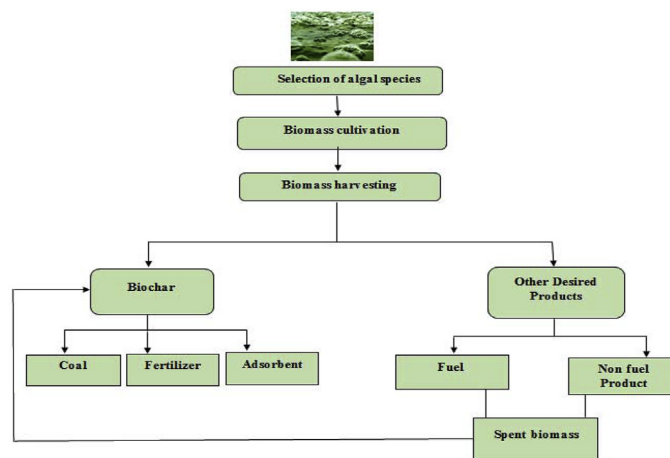


Fig. 2. Production of various by products using algal biomass during bio-refinery approach.

Table 1 Comparison of biochar yield from different thermochemical methods using various algal species.

Algal species	Method of biochar production	Temperature (°C)	Biochar Yield (% wt)	Applicability	Reference
<i>Chlamydomans reinhardtii</i>	Slow pyrolysis	350	44 ± 1	Nitrogen releasing slow fertilizer	Torri et al., (2011)
<i>Spirulina</i>	Slow pyrolysis	900	25.96	Fuel, Soil amendment	Chaiwong et al., (2012)
<i>Cladophora</i>	Slow pyrolysis	900	32.21	Fuel, Soil amendment	Chaiwong et al., (2012)
<i>Spirogyra</i>	Slow pyrolysis	900	18.61	Fuel, Soil amendment	Chaiwong et al., (2012)
<i>Arthrospira platensis</i>	Hydrothermal carbonization	190	36.7 ± 1.3	Fuel, N source (biofertilizer)	Yao et al., (2016)
<i>Chlorella vulgaris</i>	Fast pyrolysis	500	31	Biofertilizer	Wang et al., (2013)
<i>Chlorella vulgaris</i> FSP-E	Fast pyrolysis	500	26.9 ± 4.09	Enhance soil fertility	Yu et al., (2018)
<i>Chlorella vulgaris</i> ESP-31	Wet torrefaction	160–180	61.7–52.6	Fuel	Bach et al., (2017b)
<i>Oedogonium intermedium</i>	Slow pyrolysis	450	29	Used as biofertilizer	Yao et al., (2016)
<i>Scenedesmus dimorphus</i>	Pyrolysis	300–600	36	Soil amendment	Bordoloi et al., (2016)
<i>Chlamydomans</i> sp. JSC4	Torrefaction	200–300	93.9	Fuel	Chen et al., (2016)
<i>Laminaria japonica</i>	Slow pyrolysis	200–800	78.34–27.95	Metal removal efficiency, Soil amendment	Wang et al., (2013)
<i>Cladophora glomerate</i>	Fixed bed pyrolysis	400–600	44–31	Fuel, Biofertilizer	Norouzi et al., (2016)
<i>Laminaria digitata</i>	Fluidized bed pyrolysis	500	29–36	Bio-oil, Biofertilizer	Yanik et al., (2013)
<i>Fucus serratus</i>	Fluidized bed pyrolysis	500	29–36	Bio-oil, Biofertilizer	Yanik et al., (2013)

algal biomass and to reduce high cost of production, harvesting and downstream processing, algal waste leftover was converted into the biochar and used for resource recovery from wastewater where Congo red was adsorbed onto the biochar surface. The maximum adsorption of Congo red dye occurred at 90 mg/l of initial dye concentration (Nautiyal et al., 2016). Cole et al. (2017) studied *Oedogonium intermedium* (freshwater macroalga) to recover dissolved phosphorous (P) and nitrogen (N) from municipal wastewater. Kidgell et al. (2014) collected freshwater macroalga *Oedogonium* from coal-fired power station and cultivated it and converted it into biochar which was used as biosorbent for 21 metals and metalloids found in an effluent produced from coal-fired power station. *Cladophora glomerata* biochar was studied for the recovery of Cr(III) ions in a single-metal system and a multi-metal system having Cr(III), Zn(II) and Cu(II) ions at different pyrolysis temperatures of 300, 350, 400 and 450 °C. With increase in pyrolysis temperature, biosorption property increased twice at 450 °C as compared to 300 °C. The multi-metal system with artificial wastewater containing Cu(II), Zn(II) and Cr(III) ions at 450 °C removed 50% Cr(III) ions, 37% Cu(II) ions and 92% Zn(II) ions (Michalak et al., 2019).

3.1. Algal biochar production

Biochar is a carbonaceous material which can be obtained from the organic biomass such as agricultural crop leftover (Preston and Schmidt, 2006; Knicker, 2007), wood waste (Ghani et al., 2013), animal manure (Touray et al., 2014), forestry residue (Gaskin et al., 2008), microalgal biomass (Yu et al., 2017a) etc. by thermal decomposition under limited supply of oxygen or in complete absence of oxygen (Amin et al., 2016; Yu et al., 2017a). Algal biochar can be formed from algal biomass by various thermochemical processes like pyrolysis, torrefaction and hydrothermal carbonization (Yu et al., 2017a; Gan et al., 2018). These processes change the physical state and the chemical composition of the biomass irreversibly (Qambrani et al., 2017). Biochar produced along with its yield through different thermochemical methods from different algal species are shown in Table 1. Each one of them has been discussed shortly.

3.1.1. Pyrolysis

It is the thermochemical process of biochar formation from biomass under an anaerobic environment at a higher range of temperature varying from 400 to 600 °C (Chen et al., 2015). The structural composition of biomass i.e., hemicelluloses, cellulose, pectin and lignin go through depolymerization, crosslinking and

fragmentation during pyrolysis and the biomass gets transformed into biochar along with small quantities of liquid products and bio-oil; bio-syngas and other condensable and non-condensable gasses (Lee et al., 2020). Various pyrolysis reactors operate on the same basic principle influenced by O₂ availability. However, the desired final products differ because of the differences in other factors such as pressure, heating rate and residence time (Qambrani et al., 2017). Pyrolysis method can be of the following types based on the factors such as residence time, temperature, heating rate, yield and composition of the biochar produced, fast and slow pyrolysis, microwave assisted pyrolysis and catalytic pyrolysis.

3.1.1.1. Slow pyrolysis. It is the standard procedure of making biochar through heating of the biomass at a temperature around 300–700 °C for a longer period to increase the biochar yield (Duku et al., 2011; Murugan and Gu, 2015; Yu et al., 2017a). It is a conventional method of biochar production from biomass and shows more yield when compared to other methods. The product formed is more feasible and reliable for agricultural use (Yu et al., 2017b). Different types of reactors have been used for biochar production such as agitated drum sand rotating kilns (Duku et al., 2011). This process is characterized by long residence time (hours to days) and slow heating rate (0.01–2 °C s⁻¹) and the production of equal compositions of solid, gas, and liquid products (Sohi et al., 2009). Slow pyrolysis is inexpensive and simple, which can be utilized from small scale to farm based production of biochar (Song and Guo, 2012).

3.1.1.2. Fast pyrolysis. In this process, biomass is subjected to moderate temperature (500–1000 °C), fast heating rate (>2 °C s⁻¹) and short residence time (<2 s) (Bridgwater, 2012; Yu et al., 2017b). Biochar (12%) also produces high yields of bio-oil (75%) along with non-condensable gases (13%) (Duman et al., 2011). The main focus of fast pyrolysis is the production of high yields of bio-oil rather than solid or any gaseous product. The bio-oil has the application as an energy carrier (Bridgwater, 2012). The bio-oil produced have heating value half that of the conventional fuel oil and is dark brown in color and has a characteristic smoky odor (Lu et al., 2009). Various factors such as feedstock type, residence time, temperature, ash content, particle size and biochar separation method influence bio-oil yield (Velden et al., 2008). Biochar produced from fast pyrolysis has more conjugated aromatic structures (Lehmann and Joseph, 2009). Slow pyrolysis process produces biochar with much longer particle retention time, on the other hand, fast pyrolysis processes produce partially pyrolyzed biochar components (Qambrani et al., 2017).

3.1.1.3. Microwave-assisted pyrolysis. It is the heating of biomass by using electromagnetic waves having the temperature of 500–800 °C. It is more efficient than slow pyrolysis (Du et al., 2011). This pyrolysis method shows uniform heating of biomass particles; there is no need for agitation and instantaneous response occurs for quick startup and shut down and these add to their advantages (Borges et al., 2014). This process has gained great attention over the past five years with the focus on its development, theory and its principle and its response to different types of biomass (Beneroso et al., 2013). The microwave pyrolysis as compared to the conventional pyrolysis is more effective, rapid, energy efficient, homogeneous and selective (Motasemi and Afzal, 2013). The microwave uses electromagnetic energy in the range of 3×10⁸ to 3 × 10¹¹ Hz frequency and 1 to 10⁻³ m wavelength (Motasemi and Afzal, 2013). The microwave works on two mechanisms namely, dipolar mechanism and ionic conduction (Zhang et al., 2017). Feedstock absorbs microwave energy or is made to absorb with the help of absorbers, where tan δ value less than 0.1 represents low absorbability and

intermediate microwave absorbability is represented by values between 0.1 and 0.5 whereas more than 0.5 represents high microwave absorbability (Zhang et al., 2017). Macroalgae are strong absorbers as compared to the microalgae and hence, they are added with some other biomass or activated carbon for better efficiency (Du et al., 2011; Hu et al., 2012). This technique has been applied to microalgae and another lignocellulosic biomass rather than on macroalga (Budarin et al., 2011). As illustrated in Table 2, microwave assisted pyrolysis of the macroalga, *Gracilaria* produces high biochar yield i.e., 32.2–71.0% and low bio-oil yield (Budarin et al., 2011). On contrary, the microalgal sp. *Chlorella* produces all three products (Du et al., 2011). This method of pyrolysis favors more of gas products (Lee et al., 2020).

3.1.1.4. Catalytic pyrolysis. This process is called catalytic pyrolysis as it is performed in the presence of catalysts like Na₂CO₃, H-ZSM-5, Fe-ZSM-5 etc. It is generally performed for bio-oil production (Babich et al., 2011; Borges et al., 2014). The elemental nitrogen and sulphur contents and the yield of biochar are influenced by the temperature of pyrolysis and feedstock properties (Yu et al., 2018). The use of diverse catalysts has various effects on different feedstocks and the diversity of the chemical composition of the feedstock used makes it difficult to understand the effect on biochar yield. There are two different modes of catalyst applications, *in situ* and *ex situ*. In the latter mode, it is easier to collect biochar at the process completion (Fakayode et al., 2020).

During pyrolysis, the formation of biochar from algal biomass undergoes three stages of dehydration, devolatilization and solid decomposition. In the dehydration stage, moisture removal causes weight loss, which is followed by devolatilization in which, volatile compounds are lost and in the last solid decomposition stage, weight loss occurs slowly. In this process, CO₂ emission is also removed making it a carbon negative approach (Chaiwong et al., 2012). The regulation of pyrolysis conditions is important to get the desired phase of the product (liquid, solid or gaseous). Temperature is inversely proportional to the biochar yield and residence time where temperature plays a very important role in the biochar yield (Yu et al., 2017b). When there is increase in the temperature and decrease in the residence time there is a decrease in the biochar yield during slow pyrolysis. Low heating rate is preferred (Gan et al., 2018). Slow pyrolysis produces high quality biochar as it undergoes deep pyrolysis for a long time and all the volatiles are removed and the carbon content of the biochar increases (Wang et al., 2020). In a microalgal consortium study predominated with *Chlorella* sp., along with *Synechocystis* sp., *Scenedesmus* sp. and *Spirulina* sp., there has been a reduction in the biochar yield with increase in pyrolytic temperature from 300 °C to 600 °C (Behera et al., 2020).

3.1.2. Torrefaction

It is a thermochemical process, which is performed at 200–300 °C in an inert or nitrogen containing anaerobic environment under atmospheric pressure (Chen et al., 2015; Mondal et al., 2017). The heating rate is lower i.e., <50 °C/min and residence time is relatively longer i.e., 20–120 min (Wang et al., 2020). The main purpose of torrefaction is to produce biochar while pyrolysis can form bio-oil or biochar depending on the parameters provided (Bach et al., 2017a). A fixed bed reactor is generally used for the torrefaction process. The effect of temperature on four different biomasses (coconut shell, bamboo, wood and willow) was studied during the torrefaction process and the compositional changes were observed. At 240 °C, hemicellulose decomposed whereas cellulose decomposed at 280 °C (Gabhane et al., 2020). During torrefaction, about 30% of the biomass is transformed into torrefied vap (IPCC, 2014) or (Akbari et al., 2020) whereas the solid product is

Table 2
Comparison of biochar yield of different algal species from different pyrolysis processes along with liquid and gas yields.

Type of pyrolysis	Algal species	Pyrolysis temperature (°C)	Pyrolysis Time (min)	Heating rate (°C/min)	Solid product yield (wt. %)	Gas product yield (wt. %)	Liquid product yield (wt. %)	HHV (MJ/Kg)	References
Slow pyrolysis	<i>Chaetoceros muelleri</i>	500	–	10	53	14	33	BS:1.2	Ahmed et al., (2018)
	<i>Synechococcus</i>	500	–	10	44	18	38	BS:1.4	Ahmed et al., (2018)
	<i>Dunaliella tertiolecta</i>	500	–	10	63	13	24	BS:2.4	Ahmed et al., (2018)
	<i>Gracilaria</i>	450	60	–	59.8–61.8	–	–	B:11.1–16.1	Roberts et al., (2015)
	<i>Undaria</i>	450	60	–	60.3–62.4	–	–	B:10.7–14.7	Roberts et al., (2015)
	<i>Eucheuma</i>	450	60	–	57.2–61.7	–	–	B:14.6–17.2	Roberts et al., (2015)
	<i>Kappaphycus</i>	450	60	–	54.1–59.2	–	–	B:13.0–17.8	Roberts et al., (2015)
	<i>Sargassum</i>	450	60	–	49.0–61.9	–	–	B:11.8–13.5	Roberts et al., (2015)
	<i>Spirulina sp. Powder</i>	450–600	60	8	31–32	24–27	40–45	BO:21.68	Chaiwong et al., (2013)
	<i>Minaria japonica</i>	300–600	60	–	39–52	15–30	28–35	AQ:12.24 OP:33.57	Bae et al., (2011)
	<i>Porphyra tenera</i>	300–600	60	–	35–60	10–20	30–48	AQ:6.75 OP:29.74	Bae et al., (2011)
	<i>Undaria pinnatifida</i>	300–600	60	–	40–60	15–25	22–40	AQ:9.56 OP:23.33	Bae et al., (2011)
	Fast pyrolysis	<i>Saccharina japonica</i>	350–500	2s	–	31.9–40.9	19.4–37.0	31.2–40.9	BO:33.0 –33.2 B:11.8–12.4
<i>Chlorella</i>		500	1.5s	–	29.0	17.3	53.9	BO:25.5	Wang et al., (2013)
<i>Sargassum natans</i>		400–600	–	–	46.9–52.9	15.3–24.1	28.8–33.7	–	Wang et al., (2013)
<i>Enteromorpha clathrata</i>		400–600	–	–	40.2–51.0	14.9–22.6	34.1–41.2	–	Wang et al., (2013)
<i>Chlorella vulgaris</i> remnants		500	–	–	31	10	53	BO:24.57	Wang et al., (2013)
Microwave-assisted Pyrolysis	<i>Chlorella protothecoides</i>	500	2–3s	600 °C/s	54	29	17	BO:30	Miao et al., (2004)
	<i>Porphyry</i>	400–700	20	–	10.2–12.2	85.6–87.1	2.2–3.0	BO:2.4–3.3 B:13.8–18.2	Hong et al., (2017)
	<i>Spirulina</i>	400–700	20	–	5.1–9.6	80–84	6.6–13.1	BO:2.9–3.3 B:13.5–14.4	Hong et al., (2017)
	<i>Chlorella</i>	400–700	20	–	5.3–11.6	79.3–84	8.2–15.4	BO:3.8–5.6 B:13.1–16.3	Hong et al., (2017)
	<i>Algae Meal</i>	750	60	–	27.83-	37.15	35.02	BO:27.54 B:24.23	Ferrera-Lorenzo et al., (2014)
Catalytic pyrolysis	<i>Scendesmus almeriensis</i>	400–800	–	–	26.9–44.5	14.5–57.5	15.6–41.0	–	Beneroso et al., (2013)
	<i>Gracilaria</i>	100–300	–	–	32.2–71.0	–	2.9–16.1	–	Budarin et al., (2011)
	<i>Oscillatoria</i>	550	120	20	43.05	26.25	33.33	BO:16.66 B:16.14	(Kawale and Kishore (2019)
	<i>Enteromorpha clathrata</i>	550	–	–	45.20–46.80	17.60–19.34	35.06–35.60	–	Wang et al., (2018)
	<i>Gracilaria gracilis</i>	500	30	–	35.6	27.1	37.3	–	Norouzi et al., (2017)
	<i>Laminaria japonica</i>	500	60	–	42.12	25.1–31.2	25.1	–	Lee et al., (2014)
	<i>Chlorella</i>	500	–	–	30.1	25.4	45.1	BO:28.2	Campanella and Harold, (2012)
	<i>Nanochloropsis sp. residue</i>	300–500	120	10	20.1–57.0	12.9–35.7	30.8–45.8	BO:32.2	Pan et al., (2010)

AQ: Aqueous phase, OP: Organic phase, B: biochar, BO: Bio-oil, BS: Bio-syngas.

the major product produced i.e., from 90% of the biomass (Wang et al., 2020). Physiochemical characteristics of the biomass including moisture content, ash content and higher heating value affect the quality of the torrefied biochar. The moisture content majorly influences the energy input of the process, which is reduced up to 61–68% during torrefaction (Akbari et al., 2020). The biomass feedstock composition affects the biochar yield which is composed of cellulose, hemicellulose and lignin. Biomass having hemicellulose produces the lowest yield (Chen et al., 2019).

Torrefaction is of two types namely, dry and wet torrefaction depending upon product distribution, process conditions and plant configuration. In dry torrefaction, biomass is pre-dried and then, subjected to torrefaction. It is sometimes known as slow pyrolysis, dry carbonization or mild pyrolysis. It takes place at temperatures of 250–350 °C and the residence time of 30 min to several hours with heating rates of less than 50 °C/min in an inert environment. The products formed are solid and vapor phases (Bach and Skreiberg, 2016). In wet torrefaction, hot compressed water is used, which produces biochar of high calorific value and having good hydrophobicity (Bach et al., 2017b). The products formed are mostly in solid phase along with the liquid (bio-oil) and gaseous (CO₂) byproducts (Bach and Skreiberg, 2016). Wet torrefaction reduces the energy cost of pre-drying, which is required in the dry method. Wet torrefaction produces more energy dense biochar than dry torrefaction. The yield of the solid torrefied biochar decreases when temperature and residence time increases (Gan et al., 2018). The effects of torrefaction on microalgae differ from those on lignocellulosic biomass due to their chemical constituents i.e., carbohydrates, proteins and lipids and torrefaction parameters such as reaction time, temperature and residence time. When *Chlorella Vulgaris* was subjected to torrefaction in a fixed bed tubular reactor at 150–300 °C for 15–60 min, the yield was 90 wt% at 250 °C while it reduced to 50 wt% at 300 °C indicating the influence of torrefaction temperature on mass yield (Phusunti et al., 2018).

3.1.3. Hydrothermal carbonization (HTC)

When pyrolysis is performed at the low temperature of 130–250 °C in water under self-generated pressure (10–40 bar) for 1–6 h, it is termed as Hydrothermal Carbonization (HTC) or hydrothermal pyrolysis and the char produced is termed as hydrochar (Libra et al., 2011; Titirici et al., 2012; Arun et al., 2020). Hydrochar obtained has controlled porosity, have spherical particles, have controlled electronic properties and surface chemistry and can be described as carbon negative approach (Titirici et al., 2012). Hydrochar being wet has high potential to be used as soil ameliorant as it has a reduced risk of fungal degradation and dust losses (Libra et al., 2011). Hydrochar produces more solid yield as compared to dry pyrolysis. It also shows high O/C and H/C ratios than dry pyrolysis (Libra et al., 2011). The type of method used to produce the biochar determines the yield of biochar. It is difficult to analyze which method is best to produce the biochar but so far slow pyrolysis is considered to be the feasible method for soil amended biochar on the basis of higher yield produced in this method (Yu et al., 2017b). This can also be inferred from Table 1 and Table 2 where biochar and solid product yield from different production methods has been discussed. Arun et al. (2020) studied hydrothermal carbonization on microalgal biomass and it had 41–55 wt% carbon content, which increased in the biochar to 85.3%. The biochar yield obtained was around 3 g/20 g of biomass at the temperature of 350 °C (Arun et al., 2020). The different algal biochar yields through different production methods for soil amendment are shown in Table 1.

3.2. Algal biochar properties and its fertilizer potential

The physical and biological properties of soil can be modified by biochar, which helps to attain better plant growth (Duku et al., 2011). The use of biochar as an agricultural soil amendment has gained much attention over the past few years. Biochar addition to soil has been widely reported to provide various benefits such as enhancement of the soil carbon pool, increase in rhizosphere microbial biodiversity, improvement in crop yield and thus, mitigation of greenhouse gases emission (Adams et al., 2020). The phenomenon of *terra preta* soil in Amazonia has attracted a lot of attention to use biochar for sustainable agriculture. *Terra preta* is one of the less fertile, highly weathered soil of Amazonia. *Terra preta* soil is highly rich in nutrients such as P, N, K, Ca, Mg, K, Zn etc, which are several times more than the surrounding soil. It is known to be originated due to biochar addition coming from naturally occurring forest fires or anthropogenic activities (Glaser and Birk, 2012). With the amazing property of the algal biochar coming from the nonarable land with high yield and having very good physical and chemical properties, it has been proved to be useful for maintaining sustainable agriculture. Algal biochar shows the property of cation exchange capability (CEC), which is defined as the ability to adsorb cations (Yu et al., 2017a). CEC is beneficial for soil improvement as it increases the retention of nutrients that can be available to plants (Libra et al., 2011). The following section gives an account of some important techniques to study the surface properties of biochar such as proximate analysis, ultimate analysis, and FTIR studies to study its application as a potential fertilizer.

3.2.1. Surface properties

The temperature of the pyrolysis influences the surface properties of the biochar. The higher temperature leads to better surface properties and pore volume (Gan et al., 2018). The surface area and porosity are the most important properties of the biochar to be used as soil ameliorant and water adsorbent (Jindo et al., 2014). The surface area of *Scenedesmus dimorphus* biochar also increased from 1.7 to 123 m²/g when the temperature of biochar production increased from 300 °C to 500 °C (Bordoloi et al., 2016). The species and the origin of the species also influence the surface area of the biochar produced (Jindo et al., 2014). A study reported *Eucheuma* showing at around 35 m² g⁻¹ surface area obtained from South Sulawesi and 30.03 m² g⁻¹ surface area obtained from java (Jindo et al., 2014). The microalgal biochar was subjected to Brunauer-Emmett-Teller (BET) analysis and it was revealed that the microalgal biochar was composed of small cracks having the pore volume of 0.01 cm³/g and the pore size of 10 μm. The surface area of the biochar was 117 m²/g (Arun et al., 2020). Both scanning and transmission electron microscopy provide data about the size, morphology, and composition of the biochar. The physical properties of biochar such as surface charge, surface area, water holding capacity, porosity, bulk density and particle size etc affect the biochar ability to be used as soil ameliorant (Amin et al., 2016).

3.2.2. Biochar production yield

The biochar production yield is very much dependent on the temperature provided and the time of residence. It decreases with the increase in temperature and residence time (Yu et al., 2017a). With the increase in the pyrolysis temperature from 300 to 600 °C, biochar yield of *Scenedesmus dimorphus* reduced from 36.0% to 22.4%. The decrease could be due to the decomposition of the biomass at higher temperature or due to dehydrogenation and dehydration of hydroxyl groups (Bordoloi et al., 2016). The algal biochar yield has been reported lower than the other feedstocks.

The high ash content in the char and different compositions of the biomass could have led to the lower yield (Ronsse et al., 2013). For better biochar yield, all the operational parameters should be focused on correctly. Biochar yield from different processes is discussed in Tables 1 and 2 as previously mentioned.

3.2.3. Fourier transform infrared spectroscopy

The technique of FTIR is executed to determine the different functional groups present on the biochar. The aliphatic and aromatic carbon compositions of the biochar are studied as C–H stretching peaks, which are influenced by the charring temperature. The biochar produced at lower temperature contains more amount of volatile carbon, which is suitable for increasing soil fertility (Jindo et al., 2014). Through FTIR, the composition of the biochar produced can be compared with the biomass used as well as the effects of different conditions can also be measured (Yu et al., 2017a). Yu et al. (2018) reported that the pyrolysis process would affect the functional groups of the biochar. The high temperature of the pyrolysis destroys C=O, C–O, C≡C and N–H functional groups in the biochar of the microalgae while the carboxylic O–H group remains intact in the biochar. The FTIR spectrum of the *Chlorella vulgaris* hydrochar revealed the functional groups present on its surface. The aliphatic C–H bond was seen at 2923.5 cm^{-1} and 2852.7 cm^{-1} wave numbers in the peak while the aliphatic C–O/C–O–C was seen at 1028 cm^{-1} , the aromatic C–H bond was seen at 825 cm^{-1} wave numbers and the –COOH peak at wavenumber around 1700 cm^{-1} (Chu et al., 2020). In a study with *Scenedesmus dimorphus* biochar, FTIR spectra showed the relation of change in the functional groups present on the surfaces of the biochar and temperature. The study was done at 300, 400, 500 and 600 °C temperature. Increase in pyrolysis temperature led to the loss of the carboxylate (–COO) group resulting in the disappearance of the peaks. The aliphatic C–H stretching showed weak absorption bands at 2950 and 2850 cm^{-1} with the rise in temperature (Bordoloi et al., 2016).

3.2.4. Proximate analysis

The proximate analysis gives information about the ash content, moisture content, volatile matter, pH and the fixed carbon content of the biochar. Fig. 3 shows the properties depicted by different analytical techniques. The pH of the algal biochar is alkaline, which is helpful for the stabilization of the soil heavy metals. The pH depends on the pyrolysis temperature and the feedstock characteristics. Moreover, pH and ash content showed a positive correlation as studied by Tag et al. (2016). When there was an increase in the pyrolysis temperature, the ash content and fixed carbon showed an increasing trend and the volatile matter showed a

decreasing trend (Tag et al., 2016). The ash content of the algal biochar increased from 22.9 wt% at 250 °C to 42.7 wt% at 600 °C (Tag et al., 2016). The electrical conductivity (EC) of *Scenedesmus dimorphus* biochar produced from pyrolysis increased with the increase in temperature and it is one of the most important parameters to be carefully taken into consideration before applying biochar as nutrient source because high EC of the biochar decreases the water uptake and thus causes nutrient imbalance resulting in the hindrance in the plant growth (Tag et al., 2016; Bordoloi et al., 2016). The increase in minerals like Ca, Mg, K, P, S and Zn with increase in temperature could be the possible reason in the increase in ash content of the *S. dimorphus* biochar (Bordoloi et al., 2016).

3.2.5. Ultimate analysis

The ultimate analysis gives information about the organic and inorganic elements of the biochar. The elemental composition gets altered during biochar formation. The increase in parameters such as torrefaction temperature and residence time increase the carbon content, while hydrogen and oxygen content decrease due to devolatilization and dehydration (Gan et al., 2018). The elemental composition of the biochar is also influenced by the pyrolysis temperature (Chang et al., 2015). The torrefied *Chlorella Vulgaris* showed an increase in nitrogen and sulphur contents to 11.51 wt% and to 0.76 wt%, respectively from 9.05 wt% and 0.36 wt%, respectively from raw biomass at 300 °C (Phusunti et al., 2017). In a study, the carbon content in the dried biomass 49.58% increased to 61.32% in the biochar. Moreover, O/C and H/C ratio decreased during pyrolysis due to dehydrogenation and demethanation (Yu et al., 2018). The chemical composition of the biochar is also species dependent. The C and H contents in brown seaweed are higher than red seaweed, which had higher S and K but lower P and N contents (Roberts et al., 2015). The elemental composition showed differences within the same species obtained from different locations. Particularly, C/N ratio has been shown important for biochar to be useful in soil fertility. C/N ratio in *Chlorella vulgaris* FSP-E dried biomass (5.04 (wt/wt)) increased to 6.28 (wt/wt) according to a study (Yu et al., 2018). This ratio tells us about the N mineralization property of the biochar to be used as soil ameliorant (Roberts et al., 2015). Similarly, other exchangeable inorganic elements are also present in algal biochar such as Al, Ca, Fe, Mg, K, which makes it useful to increase soil fertility (Chang et al., 2015). The elemental analysis of *Chlorella* sp. and *Nannochloropsis* biochar showed 33–50 wt% of carbon, 33–57% of oxygen, 1–5 wt% of hydrogen and 4–12 wt% of nitrogen. Biochar obtained can be used as a bio-fertilizer in agricultural lands to enhance soil carbon and replenish minerals (Borges et al., 2014).

In a study, the microalgae *Scenedesmus* sp. biochar obtained from Hydrothermal Carbonization (HTC) was used to remove phosphorous from wastewater and the spent biochar was used as a biofertilizer and tested for elemental and ultimate analysis. The spent biochar had the carbon content of 87.6 wt% and the moisture content of 36.8 wt%, respectively. It also had the bands at 3027.91 cm^{-1} due to the presence of the hydroxyl group (Arun et al., 2020). The spent algal biochar showed an increase in the tomato plant height up to 22 cm as compared to 10 cm with the control, also, the chlorophyll content of the tomato leaves increased to 24.5 mg/g, which was just 10.4 mg/g for the control. The dry weight also increased in the case of spent algal biochar to 640 mg as compared to 285 mg in case of control (Arun et al., 2020). Table 3 shows the chemical composition of different algal species obtained via different thermochemical processes. The *chlorella* algal biochar had effects on soil enzymes such as increase in the dehydrogenase activity, which helped to attain better crop yield (Palanisamy et al., 2017). In a study reported by Bird et al. (2012) the saltwater (SW) algal biochar showed high extractable nutrients and

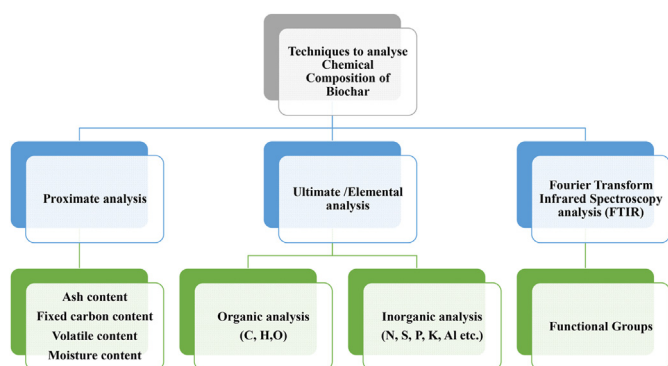


Fig. 3. Various analytical methods required for determining chemical properties of the algal biochar.

Table 3
Chemical composition of different algal biochar.

Algal species	Method of biochar production	Parameters	Chemical Composition (wt. %)							References
			N	S	C	H	O	C/N	Others	
<i>Chlorella vulgaris</i> FSP-E	Fast pyrolysis	T: 500 °C; HR: 10 °C/min	9.76	0.02	61.32	3.55	11.92	6.28	S- 0.02	Yu et al., (2018)
<i>Chlamydomonas</i> sp. JSC4	Torrefaction	T: HR:	3.34	NS	41.49	6.83	48.34	NS	NS	Palanisamy et al., (2017)
<i>Arthrospira platensis</i>	Hydrothermal carbonization	T: 190 °C; RT: 1hr; HR: 6 °C/min	8.7 ± 0.1	0.8 ± 0.1	61.9 ± 0.6	8.3 ± 0.1	NS	NS	NS	Yao et al., (2016)
<i>Scenedesmus dimorphus</i>	pyrolysis	T: 300–600 °C; HR: 40 °C/min	5.85	NS	46.82	7.85	39.48	NS	NS	Bordoloi et al., (2016)
<i>Oedogonium intermedium</i>	Slow pyrolysis	T: HR:	5.5 ± 0.1	1.0 ± 0.3	49.8 ± 0.1	NS	NS	9.1 ± 1.0	Al, Ca, Fe, K, P, Mg, Na, B, Cu, Mn, Ni, Zn, Co	Yao et al., (2016)
<i>Desmodesmus communis</i>	Pyrolysis	T: 500 °C; HR:	7.0	0.1	51.0	3.0	14.0	NS	NS	Conti et al., (2016)
<i>Chlorella based algal residue</i>	Slow pyrolysis	T: 300–700 °C; HR: 10 °C/min	10.48	NS	50.46	7.54	31.52	4.81	P:1.3, Fe:0.5, K:0.3, Ca:0.3, Mg:0.2, Mn:0.015 (wt%)	Chang et al., (2015)
<i>Chlorella vulgaris</i>	Fast pyrolysis	T: 500 °C HR:	9.43	NS	61.96	3.87	4.78	NS	P:32500, K:11140, Mg: 1346, Ca:19960, Na:593 (mg/Kg)	Wang et al., (2013)
<i>Spirulina</i>	Slow pyrolysis	T: 50–135 °C; HR: 10 °C min ⁻¹	2.57	0.07	45.26	1.24	0.28	NS	NS	Chaiwong et al., (2012)
<i>Spirogyra</i>	Slow pyrolysis	T: 50–135 °C; HR: 10 °C min ⁻¹	2.11	0.48	62.37	0.37	4.07	NS	NS	Chaiwong et al., (2012)
<i>Chlamydomans reinhardtii</i>	Slow pyrolysis	T: 550 °C; HR:	5.3 ± 0.1	<0.1	40 ± 0.1	1.4 ± 0.1	9.3 ± 0.2	NS	NS	Torri et al., (2011)
<i>Cladophora coelothrix</i>	Pyrolysis	T: 105 °C; HR:	3.3	NS	34.6	1.5	NS	10.4	Ca:277, K:145, Mg:31, Na:288, P (cmol/Kg)	Bird et al., (2011)
<i>Cladophora patentiramea</i>	Pyrolysis	T: 105 °C HR:	1.7	NS	20.3	1.2	NS	12.2	Ca: 214, K:262, Mg:62, Na:331, P (cmol/Kg)	Bird et al., (2011)
<i>Cladophora</i>	Slow pyrolysis	T: 50–135 °C; HR: 10 °C min ⁻¹	1.98	1.86	51.14	0.56	0.69	NS	NS	Chaiwong et al., (2012)
<i>Chaetomorpha linum</i>	Pyrolysis	T: 105 °C; HR:	2.4	NS	23.6	1.3	NS	10.0	Ca:21, K:475, Mg:68, Na:318, P (cmol/Kg)	Bird et al., (2011)
<i>Chaetomorpha indica</i>	Pyrolysis	T: 105 °C; HR:	1.1	NS	10.2	0.8	NS	9.4	Ca:11, K:38, Mg:17, Na:141, P (cmol/Kg)	Bird et al., (2011)
<i>Caulerpa taxifolia</i>	Pyrolysis	T: 105 °C; HR:	2.4	NS	24.8	1.2	NS	10.4	Ca:23, K:31, Mg:45, Na:812, P (cmol/Kg)	Bird et al., (2011)
<i>Cladophoropsis</i> sp.	Pyrolysis	T: 105 °C; HR:	2.8	NS	23.6	1.5	NS	8.5	Ca:25, K:118, Mg:27, Na:152, P (cmol/Kg)	Bird et al., (2011)
<i>Cladophora vagabunda</i>	Pyrolysis	T: 105 °C; HR:	2.0	NS	21.8	1.2	NS	11.1	Ca:14, K:20, Mg:14, Na:24, P (cmol/Kg)	Bird et al., (2011)

Note: NS-Not studied; T-temperature; HR-Heating rate; RT-Reaction time.

high carbon and nitrogen contents than the freshwater (FW) algal biochar. The algal biochar provides bioavailable macro and micro-nutrients required for the plant growth along with some trace elements. As studied, the growth rate of Sorghum was higher in SW algal biochar as well as FW algal biochar in comparison to other lignocellulosic (LC) biochar (Bird et al., 2012). Drought stress is one of the major problems faced by agriculturists around the globe. Algal biochar is beneficial to overcome this problem. Ullah et al. (2019) have checked different growth parameters of maize grown in water stress conditions under three different water deficit conditions (FC; field capacity, 75% FC and 50% FC) and supplied with algal biochar along with the Plant Growth Promoting Rhizobacteria (PGPR). They used various algal biochar combinations and PGPR fresh and dry weights of shoot and root, plant height, leaf area and root length numbers of leaves were increased when algal biochar was given and postharvest soil analysis also showed an increase in electrical conductivity (EC) and pH of the soil. Algal biochar also serves as a carrier for Plant Growth Promoting Bacteria (PGPR) and the combination of these two also showed a significant increase in all the parameters discussed above (Ullah et al., 2019). In a study, *Oedogonium intermedium*, a freshwater macroalga, was grown in treated municipal wastewater and converted into compost and the biochar had shown an increase in the productivity of sweet corn (*Zea mays*) variety named *Snowgold Bicolor F1* (Mr Fothergill's). The average C and N contents of the biochar were around 50% and 5.5%, respectively, which were higher than the compost i.e., 33% and 2.5%, respectively. Biochar had stable carbon content than the compost. The biochar had 5 times higher phosphorus content than the compost. The compost had a lower pH and electrical conductivity (EC) and the concentrations of most of the elements (Ca, Na, Zn, Mg, Pb, Co, Ni, Mn, Mo, Cu, P, K and B) were lower than the algal biochar produced. The significant results were found when the algal compost and the algal biochar were used together. Biochar helps the soil to bind nutrients and protect them from leaching and allows the plants to get nutrients consistently (Cole et al., 2017). The effect of algal biochar on soil improvement is less studied as compared to the effect of algal biomass directly as a soil ameliorant, therefore, more research is needed on this topic to study carbon sequestration and to mitigate global climate change and also, for helping the farmers to increase their food products without the use of chemical fertilizers and hence, further steps can be taken to achieve sustainable agriculture.

4. Algae and other lignocellulosic feedstock

The experiments of biochar amendment to soil have been in use since long. Biochar can be obtained from several other feedstock materials other than algae such as agricultural crop leftover (Preston and Schmidt, 2006; Knicker, 2007; Toor, 2020), wood waste (Ghani et al., 2013), animal manure (Touray et al., 2014), forestry residue (Gaskin et al., 2008), microalgal biomass (Yu et al., 2017a), waste sludge (Zhang et al., 2020), etc. Feedstock type and temperature of pyrolysis have effects on biochar properties to be used as a soil amendment. The choice of feedstock depends on its easy availability and low cost. The chemical and physical characterizations of feedstock are required before producing biochar. This is given by proximate and chemical analysis and comparison can be obtained (Fakayode et al., 2020). A comparison of various chemical constituents of algal biochar and other lignocellulosic feedstocks is given in Table 4. Recently, algal biomass is gaining importance over other lignocellulosic biomasses. Algal biochar differs from lignocellulose biochar both in terms of physical and chemical properties (Ronsse et al., 2013). For instance, the pore size of algal biochar ranges from 10 to 100 μm with an average of 1 μm (Pathy et al., 2020). As can be inferred from Table 4, algal biomass has more nitrogen and sulphur contents than the lignocellulosic biomasses whereas the later contains more of carbon, hydrogen and oxygen (Sellin et al., 2016; Varma and Mondal, 2017). The main composition of algal biomass is proteins, lipids and carbohydrates whereas the lignocellulosic biomasses have more of hemicellulose, cellulose and lignin (Ross et al., 2008; Fakayode et al., 2020). The surface of the biochar changes during its formation from biomass, during the process of pyrolysis, biomass particles undergoes synergistic reaction causing significant changes in their pores structure. Hemicellulose present in the lignocellulosic biomass degrades mainly at 220–315 °C while cellulose degrades at 315–400 °C. In algal biomass, the dehydration stage occurs at 200 °C and devolatilization at 200–600 °C (Fakayode et al., 2020). As we have seen above, biochar properties such as pH, CEC, ash content, surface properties, H/C ratio, C/N ratio, O/C ratio etc are important for the biochar utilized for agronomic purposes. Ash content of the algal biochar is higher than the other feedstocks and it increases with the rise in temperature. The ash content of algal biochar was 22.9 wt % at 200 °C and increased to 42.7 wt % at 600 °C which was also higher than poultry litter biochar which had 9.3 wt% ash content at 200 °C

Table 4
Comparison of algal and lignocellulosic biomass.

Feedstock Type	Feedstock Species	Chemical composition (wt. %)							References
		N	S	C	H	O	AC	MS	
Algal	<i>Enteromorpha clathrata</i>	7.05	2.45	29.42	3.96	21.76	28.56	6.80	Yuan et al., (2019)
Algal	<i>Fucus serratus</i>	2.39	1.31	33.50	4.78	34.44	11.4	18.60	Wang et al., (2013)
Algal	<i>Sargassum natans</i>	3.58	1.22	25.90	5.57	24.18	29.09	10.46	Wang et al., (2013)
Algal	<i>Undaria pinnatifida</i>	3.34	0.71	34.01	4.99	56.95	25.84	9.50	Bae et al., (2011)
Algal	<i>Laminaria japonica</i>	1.51	0.56	30.60	4.89	62.44	28.28	7.65	Bae et al., (2011)
Algal	<i>Porphyra tenera</i>	6.13	1.26	40.60	4.65	47.40	10.44	6.41	Bae et al., (2011)
Algal	<i>Fucus vesiculosus</i>	2.53	2.44	32.88	4.77	35.63	11.80	12.3	Ross et al., (2008)
Algal	<i>Laminaria digitata</i>	0.90	2.44	31.59	4.85	34.16	10.00	13.7	Ross et al., (2008)
Algal	<i>Macrocystis pyrifera</i>	2.03	1.89	27.30	4.08	34.80	18.50	8.00	Ross et al., (2008)
Algal	<i>Chorda filum</i>	1.42	1.62	39.14	4.69	37.23	9.90	13.1	Ross et al., (2008)
Lignocellulosic	Rice husk	1.20	0.14	40.20	4.68	31.77	11.41	10.60	Yuan et al., (2019)
Lignocellulosic	Corn stover	0.98	0.21	44.92	5.77	41.00	3.85	7.69	Cong et al., (2018)
Lignocellulosic	Walnut shell	1.12	1.81	45.32	5.54	46.17	5.00	5.43	Yildiz and Ceylan, (2018)
Lignocellulosic	Wheat straw	0.36	0.24	44.87	5.74	43.69	5.10	9.10	Lazdovica et al., (2017)
Lignocellulosic	Sugarcane bagasse	0.24	0.06	44.86	5.87	48.97	3.10	5.40	Varma and Mondal, (2017)
Lignocellulosic	Rapeseed cake	4.70	1.40	55.00	7.80	31.10	4.90	1.50	Smets et al., (2013)
Lignocellulosic	Almond shell	0.30	0.30	54.70	7.50	37.40	2.30	8.70	Caballero et al., (1997)
Lignocellulosic	Banana waste	0.86	0.95	43.50	6.20	42.30	11.4	7.80	Sellin et al., (2016)

Note: AC: Ash content, MS: Moisture content.

and 29.3% at 600 °C (Ronsse et al., 2013; Tag et al., 2016). Also, more ash and moisture contents of the algal biochar than the lignocellulosic biochar can be inferred from Table 4. The biochar stability in the soil is shown by H/C and O/C ratios, which indicated almost the same values in both lignocellulosic and algal biochar and showed an increasing trend with the increase in temperature (Roberts et al., 2015). Fixed carbon content can be equivalent or higher in the lignocellulosic biochar than the algal biochar depending upon the feedstock (Tag et al., 2016; Maddi et al., 2011). Microalgal biochar has more nitrogen content and other inorganic minerals such as sodium, magnesium, potassium, iron and calcium as compared to the lignocellulosic biochar (Pathy et al., 2020). The pH is considered the important property of the product, which can be used for soil improvement. The pH and ash content of the biochar are positively correlated with each other and increase with the increase in the temperature. The pH of the algal biomass increased from 8.72 at 250 °C to 13.66 at 600 °C (Tag et al., 2016). Algal biochar had more pH than Orange pomace which had pH 7.29 at 250 °C and 10.45 at 600 °C biochar as studied by Tag et al. (2016). This makes algal biochar more suitable for soil amendment purposes. Biochar produced after biohydrogen production from *Chlamydomonas reinhardtii* lost its original physical structure and showed irregular porosity where it differed from the lignocellulosic biomass that maintained its original structure. Algal biochar showed more nitrogen content ($4.4 \pm 0.2\%$), which made it more feasible to be used as slow nitrogen releasing fertilizer in the soil. Moreover, high ash content and more carbon content were observed when compared to the earlier published literature (Torri et al., 2011).

In addition, algal biochar has more extractable cations as compared to other feedstock biochars (Roberts et al., 2015). The various macroalgae studied had larger amounts of macrominerals (Na, Ca, K, P, Mg and Si) where *Fucus vesiculosus* (macroalga) had 29,350 ppm Na content and *Miscanthus* (grass) having the lowest Na content of 130 ppm. The other trace elements (Mn, Fe, Cu, Zn and Al) were also more in the algal biochar when compared to other lignocellulosic biochar with the Zn content of 70–1225 ppm in the macroalga and 12–196 ppm in the lignocellulosic biochar (Ross et al., 2008). Algal biochar also shows a very important property of cation exchange capacity (CEC), which was shown to be the highest in the algal biochar than other lignocellulosic biochar. This property as discussed above helps the plants to get nutrients consistently as and when required and this is a temperature and feedstock dependent property (Tag et al., 2016). Both lignocellulosic and algal biochar have their positive and negative properties for soil amendments. Mixing both the biochar could be a possible option for better results. Their usage for soil amendment has been on a small laboratory scale, which needs to be studied as largescale experiments to get more and more knowledge.

5. Algal biochar and environmental sustainability

Nitrous oxide (N₂O) and methane (CH₄) were the two major greenhouse gases (GHGs) which emit from agricultural soils (IPCC, 2014). The reduction of GHG emission through biochar application has the potential to mitigate global climate change. Water management, nitrogen fertilizer management, organic matter application, and cultivar selection are the key conventional strategies for the mitigation of GHG emission from the agricultural systems (Gupta et al., 2016; Malyan et al., 2019; Fagodiya et al., 2020; Kumar, 2020). The mitigation of GHG emission from the agricultural systems through biochar can be the future trending practice to be adopted by farmers globally.

5.1. Mitigation of methane emission

The application of biochar in different forms in agricultural ecosystems is followed by farmers since agricultural evaluation. In jhum and shifting cultivation, forests are burned to clear agricultural land which results in addition of biochar in soil unconsciously. The addition of algal biochar in soil increased the retention time of several limiting nutrient which enhanced soil fertility and crop economical production (Purakayastha et al., 2019). In agriculture, rice soil is the main source of CH₄ emission to atmosphere and its mitigation can play significant role in reducing global warming (Malyan et al., 2016; Malyan et al., 2020). The effects of biochar application in rice soils have been studied (Feng et al., 2012; Wang et al., 2017; Cai et al., 2018, Wu et al., 2019a; b). There are contradictory reports for CH₄ emission from rice under biochar application which was hard to do interpretations. Feng et al., (2012) studied the effects of biochar application on CH₄ emission from rice soil in field experiment and observed significant reduction in total CH₄ emission. The amendment of biochar in to rice soil doesn't inhibit the microbial activity of CH₄ production bacteria (methanogens) but significantly increased the abundance of CH₄ oxidizing bacteria (methanotrophs) in rice soil which resulted in CH₄ mitigation (Feng et al., 2012; Wu et al., 2019a; Wu et al., 2019b). Wu et al. (2019a) investigated the effect of six years old aged and fresh biochar on CH₄ oxidation in soil and found that ammonium and nitrate content in soil enhanced the CH₄ oxidation by promoting the population of methanotrophs type I and methanotrophs type II, respectively under biochar amendments. The biochar produced at higher pyrolysis temperature have more CH₄ production inhibition potential as compared to the biochar produced at lower pyrolysis temperature (Cai et al., 2018). Cai et al. (2018), conducted an incubation experiment using paddy field soil to investigated impact of biochar produced at 300 °C, 500 °C, and 700 °C pyrolysis temperature. They observed highest and lowest CH₄ production in the treatment of biochar produced at 300 °C and 700 °C, respectively (Cai et al., 2018). Application of biochar in agricultural soil enhanced the storage of carbon in the form of carbon sequestration and thus results in lower emissions of CH₄ gas to atmosphere. The contradictory studies reporting application of biochar stimulates CH₄ emissions from rice soil were also documented (Wang et al., 2017; Cai et al., 2018; Shaukat et al., 2019). Wang et al. (2017), observed that biochar produced at higher temperature (700 °C) and lower temperature (300 °C) has large surface area (161 m² g⁻¹) and smaller surface area (4.40 m² g⁻¹) respectively. Application of biochar having larger surface area enhances iron reduction bacterial population in soil which results in lower production of CH₄ as they compete with methanogenic bacteria (Wang et al., 2017). CH₄ emission dynamic under biochar production from feedstocks such as wheat straw, rice, corn, wood, has been documented (Wang et al., 2017; Cai et al., 2018; Shaukat et al., 2019), however the effect of biochar production from algal feedstock is lacking and required, which can help in combating CH₄ emission from agricultural soil.

5.2. Mitigation of nitrous oxide emission

N₂O is a 265-fold more potent GHG than CO₂, which plays a significant role in the stratospheric ozone depletion and global warming (Davidson, 2009; Fagodiya et al., 2020). The global atmospheric concentration of N₂O has increased up to 324 ppbv from 270 ppbv (before industrialization) owing to anthropogenic activities (Zhang et al., 2019). The global use of nitrogenous chemical fertilizers has increased from 12 Tg in 1960 to 113 Tg in 2010 and is the main contributor of global anthropogenic N₂O emission (Fagodiya et al., 2017). Moreover, the chemical fertilizer utilization

in the soil disturbs the natural nitrogen processes, which in turn lead to N₂O emission and soil acidification (Gao et al., 2015). N fixation, nitrification, assimilation, ammonification, and denitrification are the five main processes that are involved in N transformation in soil and N₂O emission (Fagodiya et al., 2017; Liu et al., 2019; Kumar et al., 2020a). The application of biochar potentially reduces N₂O emission. N₂O emission reduction through biochar amendment has been reported in different studies (Wang et al., 2017; Zhang et al., 2019). Due to larger surface area, biochar application in paddy cultivation increases carbon sequestration and decreases N₂O emission. In agricultural fields, the application of biochar is more effective in mitigating N₂O emission (Zhang et al., 2010; Liu et al., 2012, 2019). The surface area of *Chlorella Vulgaris* derived biochar was noticeably lower than the biochar produced from the lignocellulosic biomass (Wang et al., 2013), which might have played a role in the reduction of the adsorption capacity of ammonium (NH₄⁺) ions during its application in paddy cultivation (Chu et al., 2020). When biochar level increased from 10 to 40 t ha⁻¹, the cumulative N₂O emission reduction increased from 58 to 74% respectively as compared to the control in the rice soil of Tai Lake plain, China (Zhang et al., 2010). A Seven yearlong field experiment conducted by Liu et al. (2019) in the North Plain of China concluded that even low doses of biochar application could enhance cumulative N₂O emission reduction. The biochar application at the rate of 4.5 t ha⁻¹ increased N₂O emission reduction from 15.9 to 16.5% as compared to the control; on further increasing the biochar dose to 9 t ha⁻¹ N₂O emission reduced from where it increased from 22.8 to 26.3% as compared to the control (Liu et al., 2019). Therefore, biochar concentration is an important parameter for mitigating N₂O emission from agricultural soils. The role of algal biochar obtained from specific strains in N₂O emission from major cereal crops such as rice, wheat, and maize are limited to the best of our knowledge and it is highly desired for exploring new edge in GHGs emission mitigation from agricultural agroecosystem globally.

5.3. Carbon sequestration

Carbon dioxide is the major greenhouse gas of concern due to the combustion of fossil fuels and it pertains to serious global environmental health problems. Different approaches have been used globally to reduce CO₂ emissions such as chemical and mechanical methods and filtration (Rizwan et al., 2018). Microalgae present a wonderful approach to sequester carbon by absorbing it from the thermal power plants and converting it into different useful products such as biofuel, biodiesel, wastewater treatment, biochar, biofertilizers, adsorbents etc. (Mona et al., 2011, 2013, 2015; Wang et al., 2013) and it becomes an effective carbon negative strategy. It shows an efficient capturing of the CO₂ content of 5–15% from the flue gases as compared to the terrestrial plants, which absorb 0.03–0.06% of carbon dioxide (Li et al., 2008). Green algae have 10–15 times better solar energy absorbing efficiency than the terrestrial plants. *Spirulina* sp. fixed 53.3% of carbon dioxide for 6% CO₂ (v/v) and 45.6% for 12% CO₂ (v/v) from the flue showing the maximum average biofixation rate of 37.9% for 6% CO₂(v/v) (Morais and Costa, 2007). *Gracilaria* and *Saccharina* sp. can fix 2.3 × 10⁵ and 1.0 × 10⁶ t_{dw} year⁻¹ (dw – dry weight), respectively (Yang et al., 2015). *Chlorella Vulgaris* and *Anabaena* sp. represent high CO₂ fixation rates of 6.24 g L⁻¹ d⁻¹ and 1.45 g L⁻¹ d⁻¹, respectively (Ghorbani et al., 2014). This shows the algal potential for the mitigation of greenhouse gases such as carbon dioxide as 1.83 kg of CO₂ can be fixed by cultivating 1 kg of microalgae (Cheah et al., 2015). Kadam (2002) has reported the microalgal potential to reduce CO₂, CH₂, NO_x and SO_x. Using algae for CO₂ mitigation has the advantage of a biorefinery approach and

transport technologies are not required. It can be utilized to produce biofuels, biogas and biofertilizers (Moreira and Pires, 2016). The energy consumption and CO₂ emission during the generation of hydrogen by *Scenedesmus obliquus* were evaluated and it showed the values of energy consumption and CO₂ emission of 6–8 MJ/MJ_{H2} and -613 g/MJ_{H2}, respectively along with the microalgal productivity around 25 g m⁻² day⁻¹ (Ferreira et al., 2013). Algae are able to accumulate a large number of lipids, which represent twice more energy stored per carbon and thus, considered as a carbon neutral approach with zero CO₂ emission (Moreira and Pires, 2016). Further, algal biochar production along with the energy potential and value-added products, provides a carbon sequestering model and a soil ameliorant capable of improving the water holding capacity, nutrient status and microbial ecology of several soils (Lehmann and Joseph, 2009; Bird et al., 2012) as discussed earlier.

6. Economic perspective of algal biochar utilization

Algae with a huge potential of providing fuel and nonfuel-based products and mitigating greenhouse gases possess a constraint for the largescale production. Sustainability to be a reality, large scale algal biomass production and obtaining beneficial products from downstream processing require a huge capital investment. The extra cost adds upon harvesting the algal biomass and downstream processes, which make the process more challenging from a sustainability perspective (Kumar et al., 2020b). The costs of production of 1 kg algal biomass in a closed photobioreactor and open ponds are around 1.54 and 7.32 US\$, respectively. The costs of 1 kg oil of algal biomass grown in photobioreactors and open ponds are 24.6 and 7.64 US\$, respectively (Mahapatra et al., 2018). The most widespread commercial algal cultivation uses open pond systems. They are considered the most cost effective and economically sustainable and viable system. Several attempts have been made to cultivate algae commercially to maintain sustainable production levels and mostly success has not been achieved. Companies involved in algal batch cultivation are International Energy Inc. (Vancouver), SFN Biosystems Inc. (Calgary), Algaeneers Inc. and Algae Fuel Systems (Saskatoon). The batch culture is harvested daily, along with methane and nutrient rich biochar that produce dry biofertilizer (Pankratz et al., 2017). Algae Tec Limited (ASX: AEB) reports revenue of \$4.5 million AUD in 2014 and has claimed remarkable advancements in the productivity and CO₂ sequestration along with the reduction in capital cost savings. It has conducted hundreds of its own research trials, including laboratory scale to batch and pilot scales and has done a detailed commercial analysis for scaling up. A joint project of Algae Tec Limited in India has high yield modular photobioreactors and harvesting system (Algae tech., 2014). A comparison of commercial scale open pond raceways, tubular PBRs and flat panel PBRs estimates the costs \$6.96, \$5.85 and \$8.38, respectively per kg of dewatered algal biomass. When CO₂, nutrients and irradiation were optimized, the cost dropped to \$1.80, \$0.96 and \$0.98 per kg (Abdelaziz et al., 2013). Microalgal closed circular biorefinery has shown 35–86% reduction in cost (Judd et al., 2017). In most of the studies, there is an inverse relationship between the costs of the products obtained from algal culturing. The biorefinery approach along with CO₂ mitigation and production of biochar will surely decrease the overall production cost (Bhowmick et al., 2019). Gong and You (2014) studied CO₂ sequestration and value-added production from the algal biomass to get zero GHG emission. The CO₂ sequestration and utilization costs were reduced from \$33.65/ton of CO₂ to \$9.52/ton of CO₂. A collaborative approach by different research teams is suggested to integrate the coupling strains and associated technologies to make it more cost effective. This will enhance the incomes of high value products and production

volumes (Pankratz et al., 2017). New emerging ideas are required in this field to improve the cost benefit aspects of the algal biorefinery and cost-effective algal biochar utilization as a soil ameliorant and also to improve environmental sustainability.

7. Challenges and future prospects

There are challenges associated with microalgal cultivation, mainly in scale up. Very few researches on microalgal strains, except *Scenedesmus sp.* and *Chlorella sp.* add up to the challenges for different feedstock species (Yu et al., 2017b). Algal biochar is a cost-effective treatment for agricultural amendments where biorefinery of the algal biomass production can be utilized for further cost reductions and for maintaining a sustainable environment. The major challenge faced by this industry is high production and downstream processing costs. The algal biomass can be grown in wastewater, which also reduces the cost of nutrients required for its growth. The algal strain used is also important for the production of the final product (Santos and Pires, 2018). The challenges and problems associated with biorefinery are competition with the available biomass and raw materials as a resource, separation of the desired products without compromising other products, quality of the product produced and environmental concerns regarding greenhouse gas emission and their impacts (Bhowmick et al., 2019). This can be dealt with co-integrated process chains within the waste management system and commercial viability can be achieved through life cycle analysis (LCA) of the feedstock used and other technoeconomic assessments. Lacks of information, efficient way of the utilization of the product and market failure, are the other challenges faced (Bhowmick et al., 2019). The use of wastewater resources and the production of algal biochar along with other value-added products result in overall cost reduction. Zero waste discharge concept can be adopted for the reduction of the overall cost. Algal biochar can be mixed with other biochar depending upon the purpose of the biochar (Bhowmick et al., 2019). The guidelines of the International biochar initiative (IBI) and the European Biochar Foundations defines the biochar. IBI checks its usage for soil applications and the European Biochar Foundations generates guidelines for its sustainable production (Bolognesi et al., 2019). The certificate is produced only for a restricted range of applications to maintain circular economy circuits. To get certification and regulation requirements, the challenge lies in understanding and more control on pyrolysis process, feedstock pretreatment, influence of operating parameters and product yields, mainly focusing on product properties such as elemental analysis, surface properties, heavy metal immobilization etc (Bolognesi et al., 2019). Further, decentralization of biochar production units can be proved to be efficient to fulfill local byproduct demands and to maintain a biochar based circular economy. This also reduces long range transportation and economic impacts, will provide local employment and improves resource efficiency. Large scale application of microalgal biomass biorefinery and its usage is still in its budding stage especially, biochar application in soil amendments or biofertilizers. More understanding and research on microalgal feedstock usage and its utilization in the production of biochar for applications in the soil are required.

8. Conclusion

This review paper has discussed the potential of algae for carbon sequestration in the form of algal biomass, which could help in mitigating the current global climate change. The algal biomass can be transformed into algal biochar, which shows a huge potential to be used as a soil ameliorant and in other biorefinery approaches.

The generated algal biochar shows dependency on the method used to generate it and the parameters used during the process. Algal biochar can be a promising approach to be used as a bio-fertilizer and helps to reduce the use of chemical fertilizers, which could help in maintaining sustainable agriculture. It can be added with other lignocellulosic biochar to get better results. Moreover, it reduces the pressure on the farmers of high-cost input for their food productivity as algal biochar is a cost effective and an eco-friendly approach. Much more research is needed in this area for the sake of the climate and also, to prevent suicide attempts by the farmers of our country. Hence, it can be concluded that the algal biochar has a very huge potential of carbon sequestration and provides various environment friendly uses, which offer hope towards a sustainable environment.

Credit statement

Sharma Mona, Conceptualization, Writing – original draft Preparation, Reviewing and Editing. Neha Saini, Conceptualization, Writing – original draft Preparation, Reviewing and Editing. Sandeep K Malyan, Conceptualization, Writing – original draft Preparation. Bansal Deepak, Writing – original draft Preparation. Arivalagan Pugazhendhi, Conceptualization and Supervision, Reviewing and Editing. Smita S Kumar, Supervision, Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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