



## Review

# Revolutions in algal biochar for different applications: State-of-the-art techniques and future scenarios

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## ARTICLE INFO

## Article history:

Received 27 June 2020

Received in revised form 4 August 2020

Accepted 14 August 2020

Available online 15 August 2020

## Keywords:

Algae

Algal residue

Thermochemical processes

Pyrolysis

Biochar

## ABSTRACT

Algae are potential feedstock for the production of bioenergy and valuable chemicals. After the extraction of specific value-added products, algal residues can be further converted into biogas, biofuel, and biochar through various thermochemical treatments such as conventional pyrolysis, microwave pyrolysis, hydrothermal conversion, and torrefaction. The compositions and physicochemical characteristics of algal biochar that determine the subsequent applications are comprehensively discussed. Algal biochar carbonized at high-temperature showed remarkable performance for use as supercapacitors, CO<sub>2</sub> adsorbents, and persulfate activation, due to its graphitic carbon structure, high electron transport, and specific surface area. The algal biochar produced by pyrolysis at moderate-temperature exhibits high performance for adsorption of pollutants due to combination of miscellaneous functional groups and porous structures, whereas coal fuel can be obtained from algae *via* torrefaction by pyrolysis at relatively low-temperature. The aim of this review is to study the production of algal biochar in a cost-effective and environmental-friendly method and to reduce the environmental pollution associated with bioenergy generation, achieving zero emission energy production.

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## 1. Introduction

Biochar (BC) is a well-known carbonaceous material, formed from waste biomass by thermal decomposition in a limited oxygen environment. It provides an alternative solution for disposal of biomass-based wastes [1]. The structure and physicochemical characteristics of BC are highly dependent on the biomass composition (*i.e.*, lignin, cellulose, protein, *etc.*) and its thermochemical process (*e.g.*, pyrolysis, hydrothermal liquefaction, gasification, torrefaction, direct combustion) [2]. In general, BC with good physicochemical properties, structural stability and porous structure, as well as containing sufficient numbers of surface functional groups and ash, can be specifically designed by altering the biomass precursors and thermal conditions [3,4]. Recently, biochar has been recognized as various functional materials with the advantages of easy-to-manufacture, low cost, and high sustainability [5].

Algae, simply categorized as macroalgae and microalgae, can transform solar energy into various chemical compounds through photosynthesis [6]. Owing to their rapid growth, good

environmental tolerance, high CO<sub>2</sub> fixation efficiency, high reduction of organic wastes (*e.g.*, nitrogen, sulfur, and chemical oxygen demand (COD)), and high potential for production of numerous valuable compounds (*e.g.*, lipid, protein, pigment, and starch), algae have received much attention as potential alternative source for renewable energy, food additives, or pharmaceutical supplements, and also treatment of air pollutants (*i.e.*, CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub>, *etc.*) and wastewater (*i.e.*, organic matter, antibiotics, estrogens, *etc.*) [6–8].

Although algae-based industries have shown rapid growth, systematic studies are relatively few on methods to efficiently deal with the large amounts of algal residue/wastes to reduce their potential ecological impacts and enhance their utility, which largely hinder their commercial viability [9]. Recently, in order to reduce cost and environmental impact of algae, the waste algal biomass (*e.g.*, the biomass remaining after wastewater treatment) or algal residue (*e.g.*, the residue obtained after value-added products are extracted) were used for making functional BC by thermochemical processes, due to their specific chemical compositions and characteristics [2,10]. Compared to lignocellulose-based BC, algal BC usually possesses higher cation exchange capacity (CEC) and pH value, as well as higher contents of nitrogen and trace elements, which could be useful for improving the chemical properties required for different applications [11,12].

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However, only limited studies on chemical characterizations, surface structure and chemistry, mechanisms, and application potentials of algal BC have been reported. Yu *et al.* discussed the fabrication influences towards algal biochar production along with a comparison between the biochar derived from different feedstock, indicating the merits in algal biochar [1]. In addition, The advantages of using algal biochar as coal fuel and adsorbent were also analyzed [12]. Gan *et al.* reviewed the potential of using algal biochar as bio-adsorbent for wastewater treatment [8]. Although some of the characterizations of algal biochar with their high applicability were briefly introduced, a comprehensive understanding in the effects of various thermochemical strategies on their properties and application potential is still lacking. Therefore, this review provides an insightful discussion on the connection among the production strategies, algal biochar characteristics and following applications. Accordingly, many scientific points are still unclear that need to be clarified and addressed. This review aims to present an in-depth discussion on the potential applications of algal BC as a supercapacitor, for CO<sub>2</sub> capture, coal fuel, or wastewater handler. Overall, this review provides new insights on the developing strategies for efficiently converting waste algae/algal residue into functional algal BC for different energy/environmental fields. The corresponding chemical properties and working mechanisms of algal BC have also been elucidated to enhance its applicability.

## 2. Production of algal biochar

### 2.1. Biochemical compositions of waste algae/algal residue

Waste algae/algal residues are mainly composed of proteins (6%–70%), lipids (2%–50%), and carbohydrates (4%–64%). Their proportions are mainly affected by algal species and culturing conditions, and can be manipulated through genetic engineering

[13]. Variations in chemical composition significantly affect the production and subsequent use of algal BC products [14]. Moreover, another factor that impacts the algal BC is pyrolysis temperature. The thermal treatment of algal biomass was found to cause dehydration (25–200 °C), decomposition of carbohydrates and proteins (200–500 °C), dissolution of lipids (350–550 °C), and decomposition of other components of algal biomass (550–800 °C) (Fig. 1) [15].

Proteins in algae disintegrate mainly into amine compounds, some of which are aromatic hydrocarbons (such as toluene, xylene, nitrile, and phenols) and N-heterocyclic compounds (such as indoles) at temperatures between 300 °C and 500 °C. In addition, some of the breakdown compounds of these proteins also exist as liquid products below 300 °C [16]. Olefins can also be formed from certain intermediates due to cracking, deoxygenation, and deamination [17]. It has been shown that nitrogen in algae mainly exists in the form of protein-N (about 90%) [18]. Between 400–600 °C, protein-N in algae can be cleaved into pyridine-N, pyrrole-N, graphitized-N, and oxidized-N through thermochemical conversion processes, which may largely affect the subsequent applications of algal biochar. The formation of pyridine-N and pyrrole-N is through deamination or dehydrogenation of amino acids. Subsequently, some pyridine-N is converted to graphitized-N [18].

Carbohydrates, in the form of polysaccharides and oligosaccharides, are abundantly present in algal cells [19]. The main products of pyrolysis of carbohydrates are anhydrosugars and furfurals, which are obtained by hydrolysis, fragmentation, and dehydration reactions. The decarboxylation and deoxygenation reactions produce ketones, aldehydes, acids, and alcohols, which can be further cracked to olefins. Cyclization reactions convert olefins into aromatics [20]. Chen *et al.* demonstrated that the highly aromatic and graphitic structure of biochar facilitated the  $\pi$ - $\pi$  interactions between the aromatic ring of pollutants and carbon structure at the surface [21].

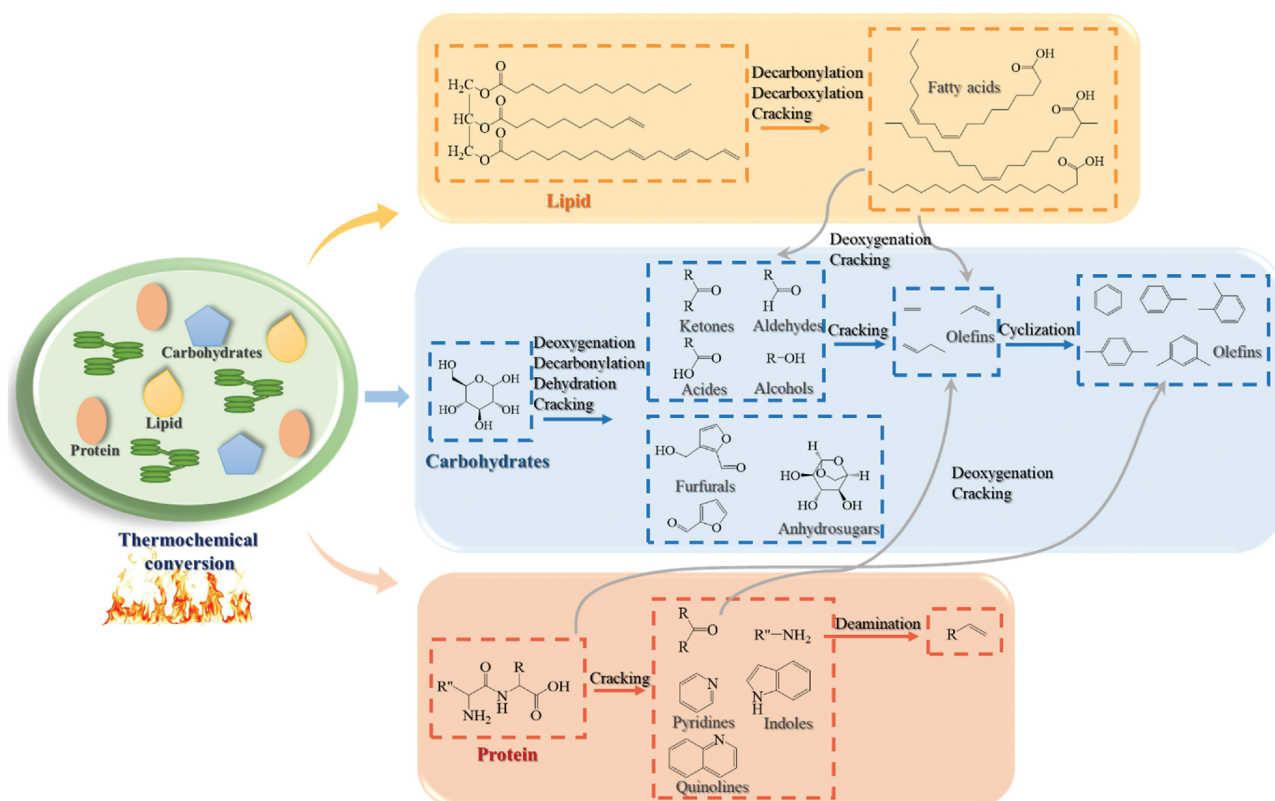


Fig. 1. Hypothetical pathway for pyrolysis of algal components.

Lipids mainly include triglycerides, free fatty acids, and steroids, which can be converted into alkanes, alkenes, and aromatic compounds by thermal decomposition [20]. During pyrolysis, triglycerides are firstly hydrolyzed or cleaved, resulting in cutting off the acyl chains from the glycerol molecule, to form long-chain fatty acids [20]. Cracking of saturated fatty acids occurs by decarboxylation during thermal treatment leading to the formation of ketones, alkanes, and alkenes. However, unsaturated fatty acids produce CO<sub>2</sub>, CO, hydrocarbons, alkanes, alkenes, and fatty acids, due to the impact on C=C bonds below 400 °C [22]. Olefins are converted to aromatics through cyclization and aromatization reactions [20]. Steroids usually disintegrate into smaller molecules, forming stable polycyclic aromatic hydrocarbons during torrefaction and pyrolysis [23].

## 2.2. Comparison of different thermochemical conversion processes

### 2.2.1. Conventional pyrolysis

Conventional pyrolysis, conducted in temperature range from 300 °C to 1000 °C, is a feasible technology for biochar conversion. It further condenses and polymerizes intermediates and maximizes the yield of solid residues [24]. The process generally involves loss of moisture, disintegration of organic structures, and slow decomposition of residual solids [2,9]. Depending on the duration of operation, conventional pyrolysis technologies can be divided into either fast pyrolysis or slow pyrolysis. Slow pyrolysis with a residence time of around 300–550 s and low heating rate of 0.1–1.0 °C/s can yield a maximum amount of biochar, while fast pyrolysis with a high heating rate of above 100 °C/s at a range of 400–600 °C can usually obtain a higher bio-oil yield [25]. Each type produces different composition of biochar, depending on the operating parameters such as temperature, heating rate, and residence time [11]. The surface structure and composition of algae do not show obvious changes, due to incomplete carbonization at pyrolysis temperature below 300 °C. The yield of algal biochar was in the range of 15–43 wt%, and the yield decreased significantly as the pyrolysis temperature increased to 350 °C [17]. When the pyrolysis temperature was increased from 500 °C to 700 °C, higher concentration of H<sub>2</sub> and lower concentration of CO were obtained, which facilitated the carbonization of algae [26,27]. When the carbonization temperature of algae was more than 700 °C, the graphitization degree, specific surface area (SSA), and electrical conductivity of algal BC improved dramatically [28]. After pyrolysis at high-temperature, the surface physicochemical properties and structures of algal BC were obtained following the release of volatile matter and gases [29,30]. The optimal temperature for pyrolysis of algal BC was decided by the practical applications of the major components and the contents of proteins, polysaccharides, and lipids in algae.

### 2.2.2. Microwave pyrolysis

Microwave pyrolysis (MWP) is a potential thermochemical process, which converts waste residue into biochar, especially wet biomass [31,32]. The moisture content of algae plays a crucial role in the pyrolysis process. Presence of moisture in the raw material helps in improving the heating rate during microwave pyrolysis. This is contrary to the conventional pyrolysis method, since water present in the raw material absorbs energy and reduces the heating rate [33]. Microwaves remove moisture from the raw material before the organics are volatilized, which increases the porosity of biochar [34]. Meanwhile, due to high microwave absorption capacity of water, heating efficiency is effectively improved [33]. In addition, MWP has other advantages, compared with conventional pyrolysis methods: (1) It can be applied for heating larger biomass particles. (2) Syngas produced at higher temperature can be used for *in-situ* generation of electricity. (3) Agitation and fluidization

are not required, which makes the process more environmental-friendly. (4) It is a more mature technology for scale-up [34]. Moreover, addition of microwave absorbers and catalysts to algal residues improves the process efficiency and increases the concentrations of specific components [34]. A previous study has shown that the biochar yield reduces with increase in temperature and shortening of residence time [35]. The calorific value of *Chlorella vulgaris* ESP-31 reached 21%, with at least 61.5% retention of biomass energy after wet torrefaction [36].

### 2.2.3. Hydrothermal process

Hydrothermal process refers to the thermochemical process of treating waste biomass from refinery with hot compressed water and is a potential pretreatment method for algal residues [37]. The density, ion dissociation constant, and static dielectric constant values of water reduce drastically under extreme environmental conditions. In particular, under conditions above the critical point of water (374.3 °C and 22.1 MPa), the reaction rate accelerates. Hot compressed water acts as a highly diffusive and soluble reactant. When this process is employed for increasing the carbon content of wet biomass, no prior drying is required. This makes it a potential alternative for the treatment of waste streams under certain conditions [1]. The thermochemical process is an appropriate technology for utilization of algae and energy recovery, due to its high organic content and moisture, as well as significantly reduced operational costs [38]. In general, hydrochar is generated through hydrothermal carbonization at 180–250 °C. With increase in carbonization temperature and pressure, hydrochar is converted to bio-oil and bio-gas [39].

### 2.2.4. Torrefaction

Torrefaction is a thermochemical process of conversion, also known as mild-pyrolysis. It typically occurs under oxygen-free as well as atmospheric pressure conditions at temperatures between 200 °C–300 °C and time period of 10–60 min [40]. Since moisture is expelled during torrefaction, the product has the attractive characteristics of lower moisture content, as well as higher calorific value and energy density [41]. Chen *et al.* demonstrated that torrefaction promoted the fuel properties of algae and decreased its reactivity by analyzing the element types, changes in functional groups, and combustion properties [42]. With decreased transportation costs, torrefaction was useful for efficiently upgrading the fuel properties of raw biomass and forming a high-quality bio-fuel from waste biomass, due to the brittle nature and better fuel properties of biomass [43,44]. Furthermore, decrease in torrefaction duration, energy consumption, and carrier gas expense can be achieved by changing the carrier gas from N<sub>2</sub> to air or other oxidative gases. This increased the energy efficiency, reduced the cost, and improved the application feasibility, except for slightly high ash content [13,45].

## 3. Characteristics of algal biochar

### 3.1. Chemical compositions of algal biochar

The content and type of algal biochar are dependent on many factors, such as pyrolysis methods, algal species, operating parameters, and activation methods, which require optimization for any specific application. The C content of algal biochar is 28.5%–59.2% and its H content is approximately 7%. The N content is between 2.5%–11%, which is dependent on the protein content of algae. Meanwhile, S is present in relatively low amounts (0.5%–1.5%) in algae. The O/C and H/C atomic ratios are used as indices for analyzing the graphitization degree, stability, and heating value of biochar [46,47]. In addition, functional groups, such as oxygen-containing groups (–COOH, –OH, and C=O) and N-containing

groups (pyridine-N, pyrrole-N, graphitized-N, and oxidized-N) with optimal atomic ratios of H/C, O/C, N/C, and (N+O)/C, show significant properties and are in huge demand [18,48]. It was reported that phenolic –OH and amino –NH<sub>x</sub> groups with abundant number of unpaired electrons would assist in the removal of pollutants. The two pairs of non-bonding electrons on oxygen of C=O may affect catalysis, since one of the pairs can serve as a nucleophile [49]. Moreover, the addition of organic/inorganic N-precursors (e.g., NH<sub>4</sub>Cl, urea, thiourea, and NH<sub>3</sub>) in pyrolysis process can modify nitrogen. The presence of N-functional groups helps in improving the alkalinity of biochar, which can be attributed to accumulation of CO<sub>2</sub> by adsorption through Lewis acid-base interactions [50]. Conversion of CO<sub>2</sub> to N<sub>2</sub> atmosphere increases the SSA and also adds many oxygen functional groups to biochar at high pyrolysis temperature [51].

The extent of carbonization and graphitization increases at higher pyrolysis temperature and with longer retention time [52]. The graphitic structure of biochar suggest that most of carbon atoms become sp<sup>2</sup> hybridized, with strong  $\pi$ - $\pi$  interactions, resulting in high electron transfer rates of biochar, which improve the performance of supercapacitors, and increase organic adsorption and catalytic oxidation [53]. Furthermore, the ash content of algal biochar ranges from 18.6%–58% including various metals and nonmetal elements. The contents of inorganic elements (e.g., K, Ca, Na, Mg, and P) in biochar increase with the increase in pyrolysis temperature. Among them, various metal ions act as active components and improve the graphitization degree and catalytic performance of biochar during pyrolysis. They also help in increasing the CEC for adsorption of metals [54,55]. Additionally, the modification of metals (e.g., Fe, Mn, Cu, and Co) is noticed as a promising method to increase the applicability applications of biochar, especially, in terms of improving the performance of supercapacitors and water purification [3,56,57]. The characteristics of biochar are dependent on different pyrolysis processes. Hence, specifically “designed algal biochar” should be considered for specific applications.

### 3.2. Surface physicochemical properties of algal biochar

The vast variations in SSA and porosity of biochar are largely attributed to the pyrolysis temperature. As the temperature was raised from 500 °C to 900 °C, the porosity of biochar increased from 0.056 to 0.099 cm<sup>3</sup>/g and the SSA increased from 25.4 m<sup>2</sup>/g to 67.6 m<sup>2</sup>/g [58]. Ho *et al.* reported that the SSA of algal biochar formed at higher pyrolysis temperatures showed higher increase [28]. Chemical activation improves the structural properties of biochar. Activation with KOH is a common way to obtain developed porous structures and generate active functional groups on the surface of biochar [59]. KOH etching caused increase in SSA and pore volume to approximately 4–5 times that of pristine biochar [60]. Sevilla *et al.* proposed one-step synthesis of hierarchical porous microalgal biochar (micro-/meso-/macroporous structures) by carbonizing the carbon precursors in the presence of activator (potassium oxalate) and commercially available inexpensive hard templated calcium carbonate nanoparticles, achieving a SSA of 3135 m<sup>2</sup>/g [61]. Furthermore, Guo *et al.* reported the use of ZnCl<sub>2</sub> as an activator during the impregnation process to further enhance the SSA of biochar [62]. Moreover, the biochar displayed a good pore structure, due to the etching effect on the biomass, when the pyrolysis process used CuCl<sub>2</sub>. It was found that a hierarchical porous structure and large SSA is beneficial for the practical applications of biochar in charge storage, CO<sub>2</sub> capture, and water purification [11].

The pH and surface charge of biochar vary with the pyrolysis temperature and alkali minerals existed in biochar, such as CaCO<sub>3</sub>, KCl, and SiO<sub>2</sub>, and this has a great impact on its subsequent

applications [63,64]. At higher temperature, the pH of algal biochar improves, due to the decomposition of acidic functional groups on biochar surface and the enrichment of alkaline minerals in biochar [54,63]. Tag *et al.* indicated that the pH of algal biochar (8.7–13.7) increased as pyrolysis temperature increased from 250 °C to 600 °C [65]. Generally, the alkalinity of biochar promoted the adsorption of CO<sub>2</sub> through Lewis acid-base interactions [50]. For the removal of pollutants from water by biochar, solution pH strongly influences the surface charge of biochar. The zeta potential of biochar increases as pyrolysis temperature increases from 400 °C to 1000 °C [5]. There was a decrease in the numbers of negatively-charged functional groups (e.g., –COO<sup>–</sup> and –OH) in biochar formed at higher temperature, resulting in a net low negative charge on the surface [52]. Additionally, as the pH of solution decreased, the zeta potential of biochar increased, suggesting that the combination of –COO<sup>–</sup> and –O<sup>–</sup> with H<sup>+</sup> could decrease the negative charge of biochar [64]. This could be attributed to the adsorption of charged pollutants and persulfate anions, thus affecting the water purification performance.

## 4. Applications of algal biochar

### 4.1. Supercapacitor

Supercapacitors are promising as energy storage devices with several advantages, such as low cost, fast charge-discharge rate, high power density, long life-cycle, and low environmental impact. Based on their difference in mechanism of action, supercapacitors are categorized into three types: electric double-layer capacitors (EDLCs), *pseudo*-capacitors (PCs), and hybrid capacitors [66,67]. In EDLCs, the mechanism of energy storage depends on electrostatic accumulation of charges at the interface between carbon-based electrode and electrolyte. EDLCs show better stability and higher conductivity, although the specific capacitance is usually lower than 400 F/g. Meanwhile, PCs mainly involve surface redox reactions of metal oxides and conductive polymers, based on a Faradaic process [68]. The specific capacitances of PCs are usually higher than 1000 F/g. However, the real-life performance is poor, due to the low conductivity of metal oxides and also the interference of particle agglomeration with redox reactions [69]. Therefore, hybrid capacitors made from carbon-based materials and metal oxides, have advantages of both, EDLCs and PCs. It presents a promising strategy for the improvement of the specific capacitance and stability of biochar. The uses of algae-based carbon materials as supercapacitors are summarized in Table 1 [70–79]. In order to increase the specific capacitance of supercapacitors, characteristics like SSA and hierarchical pores of in carbonaceous materials should be enhanced [80,81]. Zeng *et al.* fabricated a solid-state supercapacitor from a single precursor kelp along with an electrolyte, separator, binder, and electrodes to achieve high specific capacitance (277 F/g or 88.2 F/cm<sup>3</sup>) with high ionic conductivity, low interface resistance, and good stability (Fig. 2) [74]. Wu *et al.* confirmed that KOH-activated biochar prepared from *Enteromorpha prolifera* has high SSA (3345 m<sup>2</sup>/g), capacitance of 440 F/g at 1 A/g, and good cycling stability [80]. Wang *et al.* obtained carbonaceous materials from *Nostoc flagelliforme*, which displayed high specific capacitance (283 F/g) with a more porous structure, and lower internal resistance [78]. These studies suggested that KOH can accelerate the formation of active pyrrolic N. This provides *pseudo*-capacitance and significantly changes the surface characteristics and structures of the carbon product, which includes SSA, porosity, and ratio of micro/mesopores [82,83]. Sevilla *et al.* demonstrated that the presence of micropores increased the SSA as well as the charge storage capacity. Meanwhile, mesopores and macropores promoted the rapid mass transport, increased electrolyte infiltration, and promoted ion

**Table 1**  
Supercapacitor performance of algal biochars.

| Algae                         | Pyrolysis (°C) | Modification methods                               | Advantages                                                                                        | Specific capacitance (F/g) | References |
|-------------------------------|----------------|----------------------------------------------------|---------------------------------------------------------------------------------------------------|----------------------------|------------|
| <i>S. Platensis</i>           | 650–750        | KOH activation                                     | The specific capacitance and rate capability are superior than other porous carbons               | 200                        | [70]       |
| Kelp                          | 700            | NH <sub>3</sub> activation                         | Low-cost, excellent cycling stability, and high specific capacitance                              | > 360                      | [71]       |
| <i>Cladophora</i>             | –              | Polypyrrole polymerization                         | Higher energy storage capacities without significant loss of power density                        | 181–127                    | [72]       |
| Kelp                          | 600            | KOH activation                                     | Environmental-friendly and biocompatible                                                          | 277                        | [73,74]    |
| <i>Nanochloropsis salina</i>  | 550            | Co(OH) <sub>2</sub> activation                     | Increased active redox sites, reduced internal resistances, and shortened ion diffusion distances | 296–347                    | [75]       |
| <i>C. glomerata</i>           | 900            | Nitric acid activation                             | High specific capacitance and excellent cycle stability                                           | 376.7                      | [76]       |
| <i>Chlorella zofingiensis</i> | 600            | KOH activation                                     | Innovative selection and cultivation strategy to improve the capacitive performance               | 353                        | [77]       |
| <i>Nostoc flagelliforme</i>   | 600–900        | KOH/ hydrofluoric acid activation                  | More number of pores, lower internal resistance, and higher specific capacitance                  | 283                        | [78]       |
| <i>Cladophora</i>             | –              | Ni(OAc) <sub>2</sub> ·4H <sub>2</sub> O activation | High conductivity, hierarchical porosity, mechanical strength, and flexibility                    | 103                        | [79]       |

diffusivity [61]. In case of algae, the synthesis of hierarchical porous (micro-/meso-/macroporous) carbons by carbonization in a mixture containing urea, algal cells, potassium oxalate, and CaCO<sub>3</sub> at 800 °C, resulted in large SSA of 3135 m<sup>2</sup>/g [61]. It has also been demonstrated that algal biochar had significant SSA and hierarchical porous structure that reduced the distance for diffusion of electrolyte ions and electrical resistance at high pyrolysis temperature (900 °C) [28].

Additionally, biochar modified with transition metal nanostructures (e.g., Mn, Cu, Co, Ni, and Ru) has been reported to be a promising electrode material, displaying superior supercapacitor performance [56,57]. According to Zhang *et al.*, nickel foam supported the *Chlorella*-inspired CoO/C hierarchical structure, due to its excellent specific capacitance of 648 F/g at 0.5 A/g and good cycling stability [84]. Pourhosseini *et al.* revealed the synthesis of a novel supercapacitor, using Fe<sub>3</sub>O<sub>4</sub>/carbon materials, derived from *Cladophora glomerata* by treatment with KOH, HNO<sub>3</sub>, and H<sub>2</sub>SO<sub>4</sub>. This material showed specific capacitance of 3D hybrid nanoparticles of 418 F/g at 1 A/g and stable cycling performance [76]. Therefore, the supercapacitor type, physical/chemical properties, pyrolysis conditions, and activation conditions significantly affect capacitance performance of algal biochar. Additionally, the reusability and stability of carbon substrates with a wide range

of potential applications are important for promoting cyclic applications of electrode materials.

#### 4.2. Coal fuel

Algae are promising feedstock for the production of coal fuel through torrefaction (Table 2 [40,58,85–94]). In order to investigate the fuel characteristics of torrefied biochar, determination of higher heating value (HHV) index and H/C and O/C atomic ratios are required. A previous study has indicated that the HHVs of microalgae and macroalgae were 7.6–23.0 MJ/kg and 5.2–21.2 MJ/kg, respectively. They were generally lower than those of lignocellulosic feedstocks, due to lower carbon content and higher ash content in algal biomass [1]. From our preliminary experiments, it was evident that lower carbon content for algae was likely, since the remaining chemicals were acquired from the culture medium or extraction buffer (e.g., protein). Therefore, the HHV of algal residue enhances dramatically, when its ash content is effectively decreased prior to torrefaction. The carbon content of algae depends on the species, culture conditions, and culture period. Chen *et al.* reported that the HHVs of *Chlamydomonas* sp. JSC4 and *Chlorella sorokiniana* CY1 residues were 17.41 and 20.40 MJ/kg, respectively. This suggested that the lower HHV of

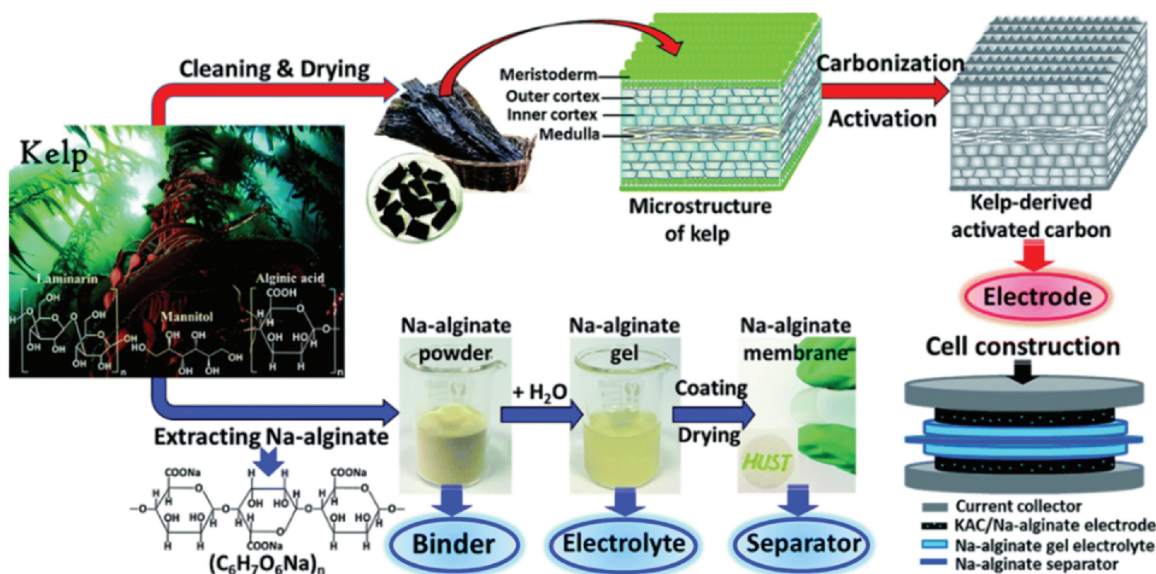


**Fig. 2.** Graphical illustration of synthesis of the material used as individual components in supercapacitors and cell construction. Reprinted with permission [74]. Copyright 2017, Royal Society of Chemistry.

**Table 2**  
Coal fuel from algal biochar.

| Algae                            | Temperature (°C) | Ultimate analysis (wt%) |             |             |             | HHV (MJ/kg) | H/C ratio | O/C ratio | Energy yield (%) | References |
|----------------------------------|------------------|-------------------------|-------------|-------------|-------------|-------------|-----------|-----------|------------------|------------|
|                                  |                  | C                       | H           | N           | O           |             |           |           |                  |            |
| Chlorella-based algal            | 300–700          | 53.59–66.23             | 1.86–4.67   | 10.23–14.12 | 13.84–25.96 | –           | 0.36–1.23 | 0.16–0.36 | –                | [58]       |
| <i>Chlorella vulgaris</i>        | 180–240          | 54.52–59.66             | 7.33–8.04   | 8.1–8.94    | 21.8–27.51  | 23.6–26.77  | 1.54–1.73 | 0.27–0.38 | –                | [85]       |
| <i>H. reticulatum</i>            | 150–270          | 30.72–42.14             | 2.52–4.5    | 32.04–45.9  | 2.37–5.53   | –           | 0.71–1.74 | 0.94–1.45 | –                | [86]       |
| <i>Gracilaria gracilis</i>       | 350              | 71.59                   | 10.19       | 7.14        | 13.06       | 36.01       | –         | –         | –                | [87]       |
| <i>Chlorella</i>                 | 280–320          | 72.89–77.67             | 12.09–12.72 | 5.74–7.34   | –           | 31.1–33.11  | 1.97–1.99 | –         | –                | [88]       |
| <i>Arthrospira platensis</i>     | 200–300          | 40.1–70.33              | 5.13–6.09   | 8.5–12.47   | 8.07–36.69  | 12.66       | –         | –         | 75.52–96.62      | [40]       |
| <i>Chlorella vulgaris</i> ESP-31 | 200–300          | 49.12–65.30             | 5.10–7.93   | 4.51–6.75   | 22.87–38.57 | 20.5–23.5   | 0.94–1.94 | 0.26–0.58 | 74.10–97.80      | [89]       |
| <i>Chlamydomonas</i> JSC4        | 200–300          | 51.58–72.60             | 4.22–7.22   | 4.00–6.49   | 16.50–37.20 | 17.6–24.77  | 0.73–1.68 | 0.23–0.54 | 74.3–99.8        | [90]       |
| <i>Cyanidioschyzon merolae</i>   | 300              | 43.52–56.86             | 4.66–5.66   | 3.36–5.57   | 30.88–42.78 | 11.74–20.40 | 0.09–0.11 | 0.54–0.98 | –                | [91]       |
| <i>Cladophora glomerata</i>      | 350              | 35.39                   | 5.18        | 5.53        | 51.63       | 13.10       | 0.15      | 1.46      | –                | [92]       |
| <i>Gracilaria gracilis</i>       | 350              | 32.69                   | 4.48        | 1.45        | 60.39       | 10.10       | 0.14      | 1.85      | –                | [92]       |
| <i>Spirulina</i>                 | 400–700          | 49.80                   | 6.60        | 11.00       | 31.90       | 13.50–14.40 | 0.13      | 0.64      | –                | [93]       |
| <i>Chlorella</i>                 | 400–700          | 51.90                   | 7.10        | 9.60        | 30.50       | 13.10–16.30 | 0.14      | 0.59      | –                | [93]       |
| <i>Chlorella vulgaris</i>        | 150–300          | –                       | –           | –           | –           | 18.14–19.30 | –         | –         | –                | [94]       |

JSC4 strain could be due to its lower carbon and higher oxygen contents [15]. In addition, the environment under which pyrolysis is conducted (e.g., H<sub>2</sub>, CO, CH<sub>4</sub>, CO<sub>2</sub>, and air) along with the co-pyrolysis strategy impacts the yields and quality of products significantly [95]. Zhang *et al.* investigated the torrefaction process in the presence or absence of O<sub>2</sub> on the formation of coal fuel (oxidative torrefaction or non-oxidative torrefaction) [96]. It was found that oxidative torrefaction could shorten the torrefaction duration to manufacture biochar having high HHV, large SSA, and excellent hydrophobicity, which could be better utilized in combustion and industrial applications (Fig. 3a). However, biochar produced by non-oxidative torrefaction showed better transportation and storage characteristics. The H/C and O/C atomic ratios were plotted on a Van Krevelen diagram to determine the fuel properties of biochar, which was basically dependent on the torrefaction temperature and duration. H/C and O/C ratios for JSC4 strain residues were reduced from 1.90 to 0.73 and 0.68 to 0.17, respectively, at 300 °C for 60 min, which met the practical requirements [90]. The solid yield from JSC4 strain residue increased from 51.3%–93.9%, at temperatures of 200 °C–300 °C, with a residence time of 15–60 min. Chen *et al.* reported that the optimal torrefaction temperature for microalgal residues was 250 °C or less. This caused lesser weight loss and higher energy densification for solid biofuel production, which could be dependent on the algae cell composition (i.e., proteins, carbohydrates, and lipids) [97]. Moreover, Ho *et al.* tested the microalgal residue for both microwave torrefaction and conventional torrefaction and concluded that microwave method saved more time and also improved the characteristics of biofuel (Fig. 3b) [98].

#### 4.3. Adsorbents

Air and water pollution are severe global threats to both environment and human health. Biochar is one of the most efficient adsorbents used for the removal of pollutants from air and aqueous environments, which include CO<sub>2</sub>, nitrogen/phosphorus, heavy metals (HMs), and organic pollutants [11,99–101]. The pollutant removal capacity of biochar is significantly affected by functional groups, SSA, constituent elements, zeta potential, and ash.

##### 4.3.1. Removal of CO<sub>2</sub>

High amounts of CO<sub>2</sub> are released into the atmosphere due to human activities, causing severe environmental problems (e.g., greenhouse effect). Adsorption is a well-known method to reduce CO<sub>2</sub> content through physical and chemical processes. Biochar derived from waste biomass, especially algae, can be used as a CO<sub>2</sub> adsorbent due to its high SSA, highly porous structure, and adequate number of surface functional groups [101,102]. Creamer *et al.* showed that biochar produced from sugarcane bagasse at 600 °C, showed high CO<sub>2</sub> adsorption capacity due to its large SSA and high N content [103]. These results suggest that SSA and N-functional groups are vital for the enhancement of CO<sub>2</sub> adsorption. The presence of N-functional groups increases the alkalinity of biochar, and improves the adsorption of CO<sub>2</sub> through Lewis acid-base interactions [50]. The nitrogen content in algae is about 1.0–12.0 wt%, which makes it a highly potential feedstock for the production of high-efficiency CO<sub>2</sub> adsorbent. Plaza *et al.* illustrated that the biochar pyrolyzed at 500–600 °C under N<sub>2</sub>, had lower O<sub>2</sub> concentration (3%–5%) and was a potential CO<sub>2</sub> adsorbent, due to its micro-porous structure [104]. A proper range of pore size would be beneficial for CO<sub>2</sub> capture. The adsorption of materials with narrow pores is based on activated diffusion, where activation energy is required so that the gas can effectively diffuse [105]. The adsorption of materials with wide pores follows Knudsen (or bulk) diffusion principles. Here, the rate of gas transport is limited by

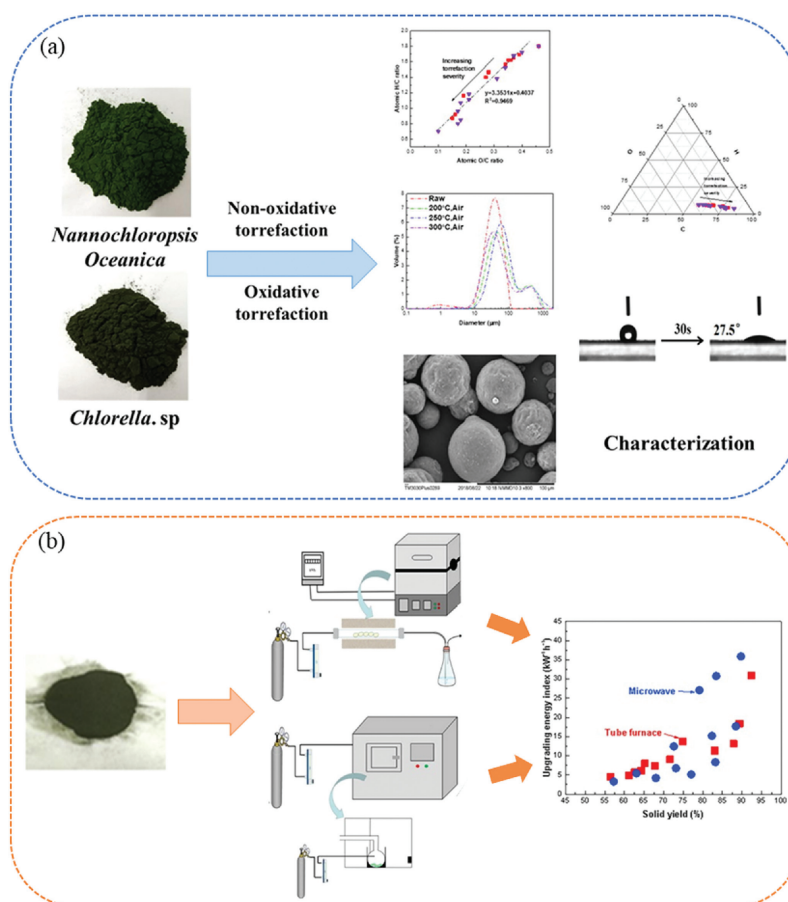


**Fig. 3.** (a) Illustration of the production of coal fuel by oxidative torrefaction or non-oxidative torrefaction processes. (b) Illustration of the production of coal fuel by microwave torrefaction and conventional torrefaction processes. Reprinted with permission [96,98]. Copyright 2019 and 2018, Elsevier.

diffusion into and out of a feeder pore system of larger pores [106]. The optimal pore diameter is supposed to be chosen with consideration of gas flow, ambient temperature and other environmental factors. Moreover, KOH can be added to further improve the SSA and form micropores extensively in the biochar [59]. Creamer and Gao proposed that optimal CO<sub>2</sub> adsorptivity was achieved using biochar with a pore diameter ranging from 0.5 nm to 0.8 nm at atmospheric pressure and room temperature. This indicated that large pore sizes can reduce the interaction between the porous structure and CO<sub>2</sub> molecule [107]. It has also been reported that CO<sub>2</sub> adsorption capacity can be improved by lowering the partial pressures [108]. When biochar was pyrolyzed at 600 °C after NH<sub>3</sub> activation, the CO<sub>2</sub> adsorption capacity was dramatically enhanced at higher temperatures, due to high SSA and abundant number of N-doping groups [109]. Overall, the total volume of micropores was the dominant factor determining the CO<sub>2</sub> adsorptivity of biochar at lower temperature (20 °C). However, the N content of biochar became the main determinant for CO<sub>2</sub> adsorption at a higher temperature (120 °C).

#### 4.3.2. Removal of inorganic ions

The mechanisms for removal of inorganic ions (*i.e.*, nitrogen/phosphorus and HMs), by algal biochar include electrostatic interactions, precipitation, complexation with surface functional groups, and ion exchange (Fig. 4 and Table 3 [28,110–123]). The zeta potential of biochar is commonly negative at neutral pH, which indicates that biochar can easily adsorb positively charged ions (*e.g.*, NH<sub>4</sub><sup>+</sup>, Pb<sup>2+</sup>, Cu<sup>2+</sup>, Cd<sup>2+</sup>, and Zn<sup>2+</sup>) [124]. The surface charge of unmodified biochar is negative, which provides non-attractive/

weak interactions with anions. Meanwhile, the modification of biochar surface and structure increases the maximum adsorption capacity. Jung *et al.* successfully synthesized granular biochar by combining a mixture of alginate solution and powdered biochar with calcium chloride solution [120]. Experimental results demonstrated that the maximum phosphate adsorption capacity was 157.7 mg/g at 30 °C, which was consistent with the Langmuir-Freundlich model. Novel SiO<sub>2</sub>-algal biochar nanocomposites were successfully synthesized by the pyrolysis of vermiculite treated algal biomass, which showed higher phosphate removal through adsorption (159.42 mg/g). The SiO<sub>2</sub> particles on the algal biochar surface had electrostatic interactions with the activated sites [125]. Moreover, biochar can be modified with many metals (*e.g.*, Fe, Mg, and Zn) to facilitate removal of pollutants [99,126]. Cu<sup>2+</sup> ions were efficiently removed from wastewater using biochar of chitosan modified magnetic kelp [112]. In the previous studies, precipitation was known to be the dominant mechanism for removal of HMs, due to the use of inorganic phases containing CO<sub>3</sub><sup>2-</sup>, PO<sub>4</sub><sup>3-</sup>, and SiO<sub>3</sub><sup>2-</sup> [54,127]. These inorganic phases are less abundant in algal biochar, resulting in low precipitation during adsorption. Cho *et al.* reported that the removal capacity of Cu<sup>2+</sup> was 69.37 mg/g using algal magnetic biochar. This could be mainly attributed to the abundance of various oxygen-containing functional groups (–COOH and –OH) [48]. Poo *et al.* prepared biochar from *Saccharina japonica* and *Sargassum fusiforme* for the efficient removal of Cu, Cd, and Zn from aqueous solution [110]. Results showed that high adsorption of HMs was attributed to the presence of a great number of oxygen-containing functional groups and higher pH. Additionally, cation exchange could be

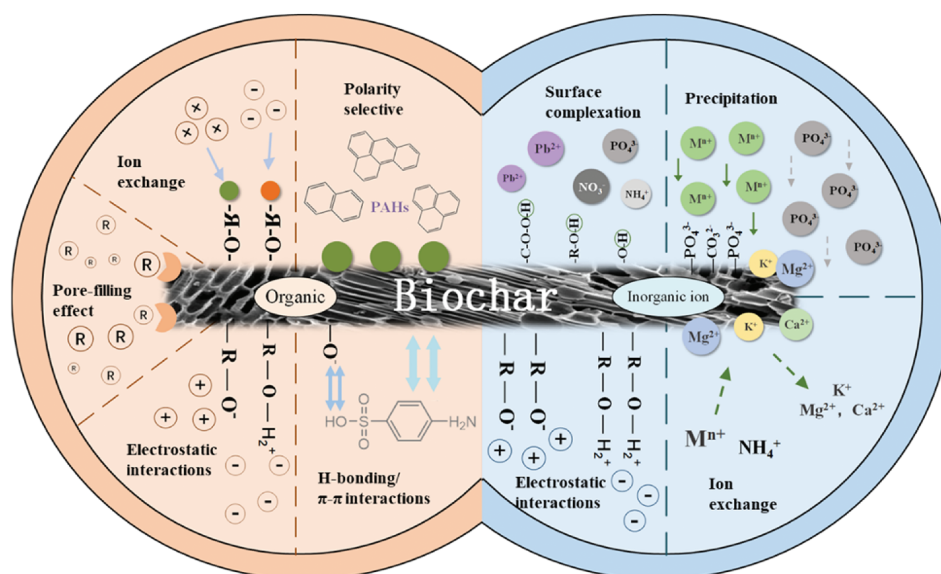


Fig. 4. Mechanisms for adsorption of organic (left) and inorganic pollutants (right) to the biochar.

Table 3  
Wastewater treatment by algal biochar.

| Algae                           | Pyrolysis (°C) | Pollutants                                                                                            | Removal capacities                 | Removal mechanisms                                                                 | References |
|---------------------------------|----------------|-------------------------------------------------------------------------------------------------------|------------------------------------|------------------------------------------------------------------------------------|------------|
| <i>Saccharina japonica</i>      | 250–700        | Cu, Cd, Zn                                                                                            | 98.60, 60.70, 84.30 mg/g           | Cation exchange                                                                    | [110]      |
| <i>Sargassum fusiforme</i>      |                |                                                                                                       | 94.10, 37.20, 43.00 mg/g           |                                                                                    |            |
| Kelp                            | 500            | Cd, Cu, Zn                                                                                            | 23.16, 55.86, 22.22 mg/g           | The oxygen-containing functional groups serve as potential adsorption site         | [111]      |
| Brown algae                     | 500            | Cu                                                                                                    | 26.99 mg/g                         | Physical adsorption, ion exchange, surface complexation, co-precipitation          | [112]      |
| <i>Chlorell</i>                 | –              | Cd                                                                                                    | 169.92 mg/g                        | Electrostatic attraction, ion exchange and surface complexation                    | [113]      |
| <i>Spirulina platensis</i>      | 450            | Congo red dye                                                                                         | 51.28 mg/g                         | Electrostatic attraction                                                           | [114]      |
| <i>Ulothrix zonata</i> algae    | 400–800        | Malachite green, Congo red, crystal violet                                                            | 5306.20, 1222.50, 345.20 mg/g      | $\pi$ - $\pi$ interaction, pore-filling effect, electrostatic interaction          | [115]      |
| <i>Chlorella</i>                | 300–700        | <i>p</i> -nitrophenols                                                                                | 204.80 mg/g                        | Strong polarity of binding sites                                                   | [116]      |
| <i>Spirulina sp.</i>            | 350–750        | Tetracycline                                                                                          | 132.8 mg/g                         | Hydrophobic, $\pi$ - $\pi$ interactions, functional groups, and metal complexation | [117]      |
| <i>Caulerpa scalpelliformis</i> | 300–500        | Remazol brilliant blue R, Remazol brilliant orange 3 R, Remazol brilliant violet 5 R, Remazol black B | 0.178, 0.231, 0.217, 0.228 mmol/g  | –                                                                                  | [118]      |
| <i>Laminaria japonica</i>       | 584            | $\text{PO}_4^{3-}$                                                                                    | 460.30 mg/g                        | Chemisorption process                                                              | [119]      |
| Marine macroalgae               | 200–800        | $\text{PO}_4^{3-}$                                                                                    | 160.70 mg/g                        | Polar, pore-filling effect                                                         | [120]      |
| <i>Spirulina</i> residue        | 400–900        | Sulfamethoxazole                                                                                      | 33.0%–100% in 45 min               | Electron-transfer regime (PDS)                                                     | [28]       |
| <i>Enteromorpha</i>             | 400–900        | Sulfamethoxazole                                                                                      | more than 95% in 90 min            | $^1\text{O}_2$ and surface electron transfer (PDS)                                 | [121]      |
| Taihu blue algae                | 800            | <i>N,N,N',N'</i> -Tetrakis (2-hydroxypropyl) ethylenediamine                                          | 98.87% in 60 min                   | $^{\bullet}\text{OH}$ ( $\text{H}_2\text{O}_2$ )                                   | [122]      |
| <i>Enteromorpha</i>             | 600–900        | Paracetamol                                                                                           | 0.0931 to 0.2472 min <sup>-1</sup> | $\text{O}_2^{\bullet-}$ and $^1\text{O}_2$ (PMS)                                   | [123]      |

another mechanism for the adsorption of HMs, due to the large number of minerals present in marine algae (e.g., Ca, Mg, K, and Na) [128]. The CEC of biochar determines the adsorptivities of cations for inorganic elements (e.g., K, Ca, Na, Mg, and P) in biochar. According to Tag *et al.*, algal biochar showed high CEC (25.6–52.6 cmol/kg) with increase in pyrolysis temperature [65]. Chen *et al.* showed that CEC of biochar at 900 °C reached a maximum value of 247.5 cmol/kg, due to the release of large amounts of alkali and earth alkali metals from ash, wherein the vacant sites were replaced by other cations [129]. Ho *et al.* reported that removal of HMs was significantly enhanced in the presence of inorganic elements, which initiated ion exchange and precipitation mechanisms [54].

#### 4.3.3. Removal of organic pollutants

Studies show that adsorption of organic pollutants depends on the characteristics of pollutants and biochar surface chemistry (Fig. 5 and Table 3). It occurs through various mechanisms such as polar-selective, electrostatic attractions, hydrophobic interactions, pore-filling adsorption/partition, ion exchange or  $\pi$ - $\pi$  interactions [5]. At high thermal pyrolysis temperature, the adsorption mechanism of biochar converts from polar-selective to pore filling property [130]. The change of sorption mechanism from partitioning to adsorption makes the sorption rate slower and then faster with the increasing pyrolysis temperature [131]. Chen *et al.* showed that algal biochar had the highest dye removal capacity at 800 °C [115]. The adsorption capacity for Congo red anion was

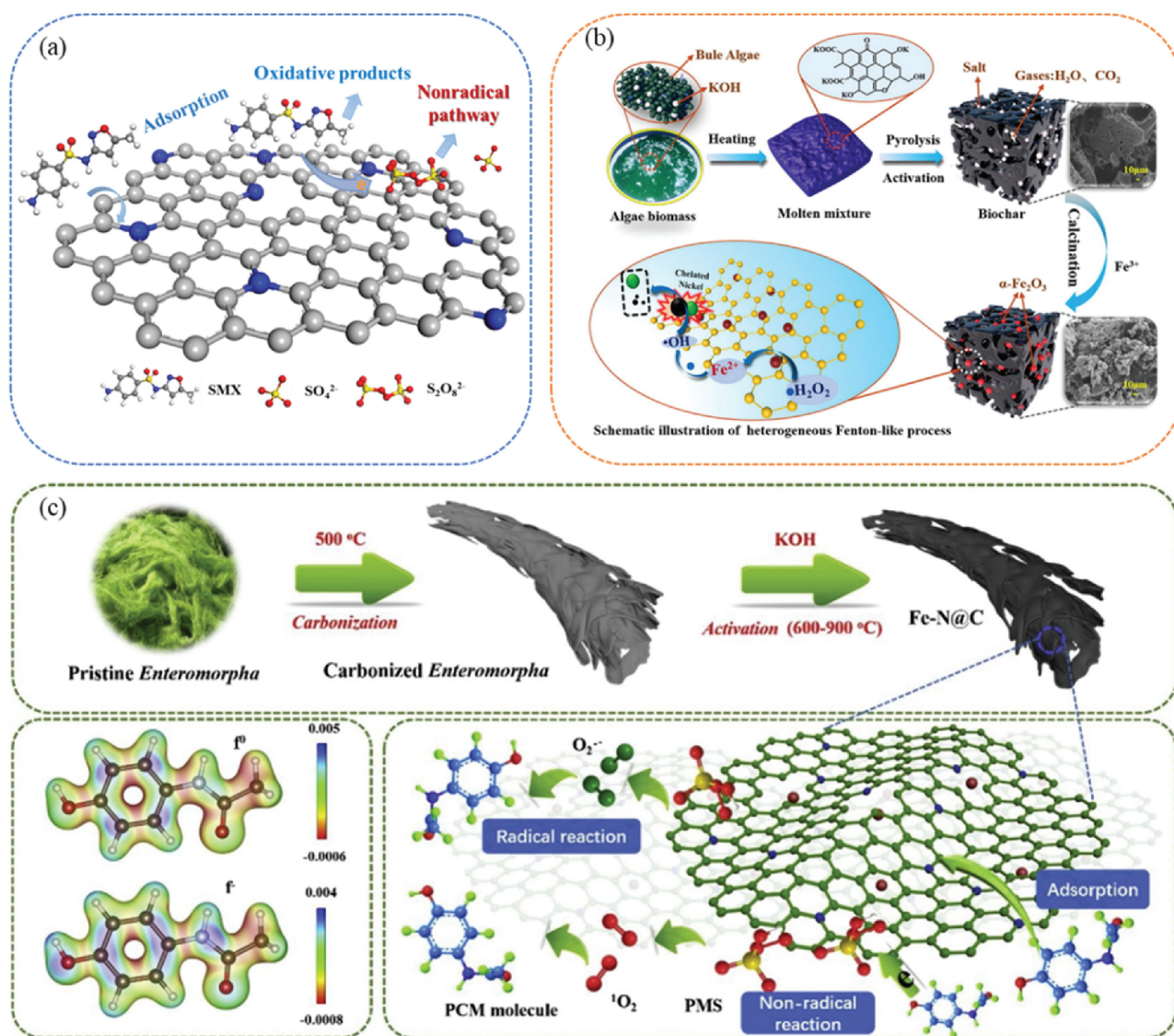


**Fig. 5.** (a) Illustration of mechanisms for catalytic oxidation of organics in SDBC/PS system. (b) Scheme for the preparation of Fe(III)-ABC-20 from blue algae and mechanism of heterogeneous Fenton-like process. (c) Scheme for the preparation of Fe-C@N and mechanism of PCM removal in Fe-N@C/PMS system. Reprinted with permission [28,122,123]. Copyright 2019 and 2020, Elsevier.

lower than those of cationic malachite green and crystal violet at neutral pH, due to electrostatic attractions. The highest dye adsorption capacity for malachite green was 5306.2 mg/g, which could be well fitted to both the Freundlich isotherm and pseudo-second-order model. Some researchers reported that the removal of ionizable organic pollutants rely on a pH-dependent sorption behavior [5,132]. It was found the adsorption mechanism at low pH was the  $\pi$ - $\pi$  donor-acceptor interaction, and transformed into a negative charge assisted H-bond at high pH [132]. Biochar formed from the *Spirulina platensis* residue was used to remove Congo red (51.28 mg/g) and was also well fitted to the Freundlich isotherm model with correlation coefficient of 99.12% [133]. Zhang *et al.* prepared biochar from *Chlorella* sp. Cha-01, which displayed higher adsorption capacity for *p*-nitrophenol, compared to that prepared from raw microalgae. This was due to the presence of sufficient number of O-containing functional groups. This could be a main factor for strong polarity, resulting in high adsorption efficiency [116].

#### 4.4. Catalysts

Advanced oxidation processes (AOPs) play an important role in wastewater treatment. Free radicals, such as hydroxyl radical ( $\cdot\text{OH}$ ), sulfate radical ( $\text{SO}_4^{\cdot-}$ ) or singlet oxygen ( $^1\text{O}_2$ ), showing strong oxidative capacities, are produced in AOPs and they can directly degrade organic pollutants [134–136]. Recently, sulfate radical-based AOPs have received widespread attention, due to their high efficiencies for degradation of organic pollutants and high selectivity in complex environmental systems.  $\text{SO}_4^{\cdot-}$  is mainly produced by activation of peroxydisulfate (PDS) or peroxymonosulfate (PMS) and displays a high redox potential (2.5–3.1 V) and long half-life (30–40  $\mu\text{s}$ ) for water purification [137,138]. Besides, sulfate radical based-AOPs (SR-AOPs) can be applied in more complex water environment and a wider pH range compared with the Fenton reaction. The solid PDS is also cheaper (0.74 \$/kg vs. 1.5 \$/kg of  $\text{H}_2\text{O}_2$ ) and more convenient to be transported and stored in most cases [139]. Generally, PDS and PMS can be activated by

physical and chemical methods such as heating, UV/solar irradiations, and transition metals ( $\text{Cu}^{2+}$ ,  $\text{Fe}^0$ ,  $\text{Fe}_3\text{O}_4$ ,  $\text{MnO}_2$ , etc.) [140–143]. More recently, carbonaceous materials (e.g., carbon nanotubes, graphene, nano-diamond) with large SSA, high resistance under complex environmental conditions, good biocompatibility, and flexible electronic properties, have been used as carbocatalysts. Among them, biochar is a better choice, due to its low cost and ease of preparation [21,144].

Ho *et al.* reported that biochar that was prepared from the intrinsic protein in *Spirulina* residue (SDBC) by *in situ* N-doping displayed high-performance of PDS activation (Fig. 5a) [28]. It was also found that the degradation performance of sulfamethoxazole (SMX) was significantly increased from 33.0% to 100% with temperature for pyrolysis of SDBC ranging from 400 °C to 900 °C in 45 min. This could be attributed to its high degree of carbonization, large SSA, and excellent conductivity. A high degree of carbonization in carbocatalysts promotes  $\pi$ - $\pi$  interactions with C=C bonds or benzene rings present in organic pollutants [145]. Meanwhile, a large SSA with high volume of pores exposes the active catalytic sites, whereas a hierarchically porous structure promotes the contact of organic pollutants or PMS/PDS with the active sites. This effectively increases the catalytic effect for the degradation and removal of organics pollutants [145]. According to Ren *et al.*, the presence of abundant number of oxygen-functional groups such as carbonyl and carboxyl groups could disturb the  $\pi$ - $\pi$  structure. The presence of oxygen-containing groups like strong Brønsted acid groups could reduce the zeta potential of materials [146]. Therefore, for high pyrolysis temperature, the surface negative charge of carbocatalysts with lesser number of oxygen-containing groups was lower enough so as to improve the adsorption of the negatively charged PDS and PMS during oxidation processes. Qi *et al.* synthesized a 3D porous graphite-like biochar, from *Enteromorpha* (EGB) by mixing with  $\text{K}_2\text{CO}_3$  at high pyrolysis temperature to activate PDS for degradation of SMX [121]. According to them, graphitic N in EGB played a significant role in the oxidation process, which could be attributed to its strong binding for PDS and SMX on adsorption. The physical and chemical modification methods improve the characteristics of biochar when activated with PDS and PMS. A new type of algal biochar composites, impregnated with  $\alpha\text{-Fe}_2\text{O}_3$  and activated with KOH for hierarchical porous structure (Fe(III)-ABC-20) was prepared from Taihu blue algae, which blooms annually, as precursor (Fig. 5b) [122]. It was found that the algal biochar activated by KOH had larger SSA (1657.8  $\text{m}^2/\text{g}$ ) than that of original biochar (17.9  $\text{m}^2/\text{g}$ ), as well abundant number of oxygen-containing functional groups on the surface of Fe(III)-ABC-20. Fe(III)-ABC-20 (0.5 g) and  $\text{H}_2\text{O}_2$  (20 mmol/L) could remove 98.87% chelated nickel efficiently and achieved the degradation of *N,N,N',N'*-tetrakis (2-hydroxypropyl) ethylenediamine. Meanwhile, Chen *et al.* demonstrated the synthesis of an environmental-friendly, economical, and high-efficient Fe/N co-doped carbonaceous material (Fe-N@C) using *Enteromorpha* by pre-pyrolysis at 500 °C. Then, the carbonized material was mixed with KOH and pyrolyzed between 600–900 °C (Fig. 5c) [123]. Also, the graphitic N derived from the inherent N in *Enteromorpha* displayed good correlation with removal of organics, as confirmed from the calculations of density functional theory (DFT). The  $\text{O}_2^{\cdot-}$  and non-radical  $^1\text{O}_2$  produced were the primary mechanisms in Fe-N@C/PMS system. Moreover, Qi *et al.* revealed that the mechanism of EGB/PDS system was dominated by radical pathway due to the persistent free radicals (PFRs) in EGB, fabricated at 400 °C. Meanwhile,  $^1\text{O}_2$  and electron transfer were the main mechanisms of non-radical pathways in EGB pyrolyzed above 500 °C [121]. The mechanism in biochar/ PDS system was similar to that suggested by Zhu *et al.* [147]. However, Ho *et al.* reported that the mechanism of SDBC/PDS system involved a nonradical pathway through electron transfer, not

relying on  $^1\text{O}_2$  and free radicals, which was determined by radical quenching tests, solvent exchange, organic selectivity, and electrochemical measurements [28]. Recently, Ren *et al.* employed various electrochemical methods like linear sweep voltammetry, cyclic voltammetry, chronoamperometry, chronopotentiometry, and electrochemical impedance spectroscopy to probe the non-radical pathway [148].

## 5. Current challenges and future opportunities

The economic feasibility of algal biochar can be enhanced by extracting specific value-added products (e.g., pigments or polyunsaturated fatty acids), prior to the preparation of biochar. Therefore, depending on the extraction method and the algal species used, the characteristics and qualities of algal biochar can vary vastly, as also its potential applications. In addition, to make algal biochar more cost-effective for wastewater treatment, the use of algae that can grow well in wastewaters is required. However, the algal broth harvested from wastewater could contain various HMs, organic pollutants, and many symbiotic bacteria, which dramatically influence its subsequent applications. In addition, the components of algae (such as proteins) vary significantly in wastewaters, which have major effect on the preparation and applications of biochar products. Overall, future research priorities should be the development of a novel engineering process and optimization of wastewater treatment for biochar, extraction of value-added products prior to the preparation of the algal biochar, as well as investigating the biochar structure and its corresponding potential applications. Till date, although there have been some reports on the relationship between biochar structure and its corresponding applications, further optimization requires the understanding of qualitative to semi-quantitative and finally quantitative relationships [66,149]. Definite relationships and their underlying mechanisms must be explored to effectively prepare biochar, including variations in raw material sources, pyrolysis technologies, and activation methods [5,101]. In addition, some studies have reported that persistent free radicals, trace HMs, and small-molecular organic compounds of biochar (such as polycyclic aromatic hydrocarbons, pesticides, polychlorinated biphenyls, polychlorinated dibenzo-*p*-dioxins, and furans, linear alkylbenzene sulfonates, and nonylphenol), could be toxic for the environment [5,150,151]. It is also essential to explore and balance the toxicity and benefits of algal biochar within the environment. Moreover, apart from pursuing the outstanding applications with the optimal operational conditions, little efforts were devoted to identifying the unexpected environmental impacts such as the consumptions of energy, materials, and chemicals associated with the emissions into air, soil, and water. Evaluation of the emerging techniques is of crucial importance at the early stage, otherwise merits of the technology can be constrained once moving toward scale-up application [152]. In this regard, life cycle assessment (LCA) can provide an impartial analysis of these environmental hotspots [153]. Therefore, the LCA of algal biochar in various applications should be further evaluated by taking into considerations of the economic efficiencies beyond the lab-scale stage and the potential trade-off in practical environmental remediation.

## Declaration of competing interest

The authors report no declarations of interest.

## Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (No. 51961165104) and the Project of Thousand Youth Talents.

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