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Electrodes derived from various food waste or biomass for capacitive deionization (CDI) application

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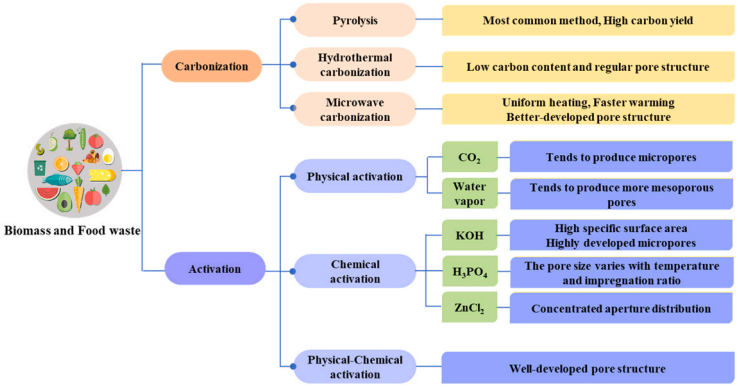
HIGHLIGHTS

- Recent progress on electrode materials prepared from biomass and food waste and their applications in CDI are reviewed.
- Food waste and biomass materials have demonstrated great potentials to be recycled into CDI electrodes.
- This collective effort in recycling food waste and biomass materials into value added carbon can contribute greatly to circular economy goals.

GRAPHICAL ABSTRACT



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ABSTRACT

The shortage of water resources makes the research of water treatment technology more urgent. Capacitive deionization (CDI) is a potentially cost-effective desalination technology whose electroabsorption capacity depends on the structure and properties of the electrode material. Biomass materials have become a research hotspot in the field of CDI electrode materials because of their abundant resources, low cost and unique structure. In this paper, the technology of CDI electrode materials prepared from biomass and food waste and their application in CDI are reviewed.

1. Introduction

Water is the indispensable basic material for human survival and production, and also a strategic economic resource. Water scarcity is increasingly affecting the ecological environment and global socio-economic development. The United Nations agencies say water scarcity is becoming the most serious resource problem of the world [1–3]. According to the United Nations World Water Development Report in

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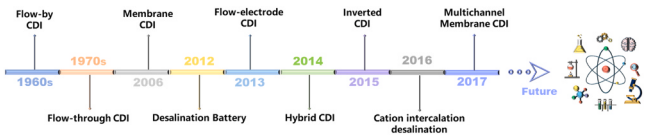

Fig. 1. Development milestone of CDI construction types.

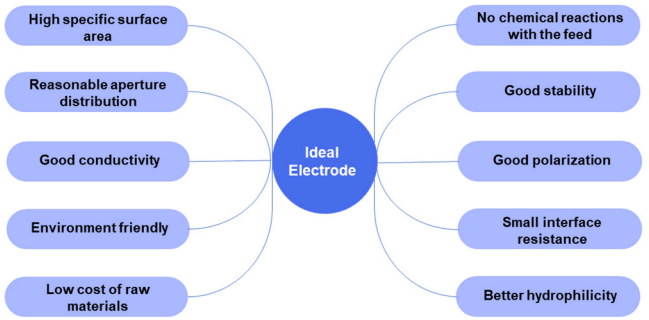

Fig. 2. Characteristics of ideal electrode.

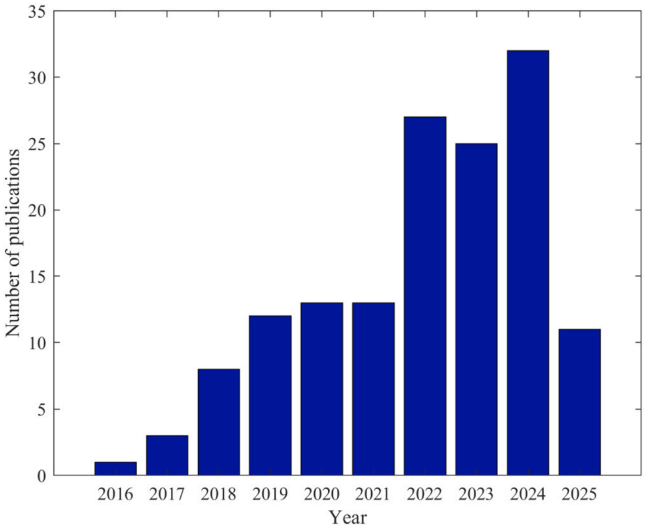

Fig. 3. Statistics of publications about using food waste/biomass derived electrodes for CDI.

2018, there will be 10 billion people in 2050 in the world, the demand of global water will grow by more than 55 % [4], and will increase to nearly 6000 km^3/year [5,6].

Traditional water treatment technology, like multi-effect distillation (MED), multi-stage flash (MSF), reverse osmosis (RO), electrodialysis (ED), forward osmosis (FO) has developed and been widely used [7,8]. However, traditional water treatment technology has different disadvantages which delay its further development [9,10]. Therefore, the development of emerging technologies has a significant role in promoting the development of water treatment technology.

Based on the theory of the electrical double layer (EDL), the capacitive deionization (CDI) technology is a new water treatment technology by using the electrostatic force produced by the charged electrode to adsorb ions and charged particles in water and enrich dissolved salts and other charged substances on the electrode surface [8,11,12]. Charged ions are removed from the solution by applying a voltage that forces them to migrate towards an electrode that has an opposite charge to them and is absorbed by the EDL generated by electrodes [12,13]. The ions attached on the electrode surface can then be released through short circuiting or polarity reversal resulting in electrode regeneration [14]. The desalination properties of CDI include salt adsorption capacity (SAC), salt adsorption rate (SAR), charging efficiency and energy consumption [15–17].

In the past few decades, significant progress has been made in the research field of CDI, with continuous improvement of theories and the emergence of various types of CDI [18]. Fig. 1 is the development milestone of CDI construction types, where different CDI system types or cell architectures can be employed to further optimize absorption performance. A previous study detailed and dated different cell architectures, with flow-by CDI and membrane CDI (MCDI) being the cost commonly used [18]. The major benefit of flow-by CDI is the simplicity of the design and operation, with low energy consumption and suitability on low-salinity water. In contrast, MCDI incorporates ion exchange membranes (IEMs), which enhance charge efficiency and extend electrode lifespan, albeit at a higher manufacturing cost.

Flow-electrode CDI (FCDI) is a further development of MCDI, utilizing flowing carbon suspensions as electrodes, with the major benefit of this method being steady production of desalted water due to a continuous ion removal process. Flow-through CDI, a variation of flow-by CDI, allows water to permeate through the electrodes. This modification requires specialized electrodes materials featuring macropores with diameters above 1 μm to ensure workable levels of feed pressure. However, flow-through CDI tends to cause higher oxidation of the positive electrode than flow-by. Hybrid CDI (HCDI), Cation Intercalation Desalination (CID) and Desalination Battery cells all remove ions via the mechanism of Faradaic. Hybrid CDI is relevant to this review, as food-waste-derived capacitive electrodes have been successfully implemented within this architecture [19]. And because of its simple structure, environment friendly, low energy consumption, anti-scaling and other advantages, CDI has been widely used in the field of water treatment [10,11,15].

The selection of electrode materials is the key to CDI technology, which directly determines its desalination efficiency and capability. Based on the study of comprehensive electrode materials. Fig. 2 shows the characteristics of ideal electrode [7,9,11,20].

Carbon-based materials, with large specific surface area and rich pore structure, are easy to form double-layer capacitance, making it the preferred material for electrode materials [21]. Over the past few decades, scientists have tried many kinds of carbon materials modification methods, to find a more suitable for the actual production of modified materials. Therefore, more carbon-based materials have been used in CDI technology, which significantly promoted the development of the field.

Traditional carbon materials used for electrodes include activated carbon, carbon aerogel, carbon nanotubes, carbon nanofibers, ordered mesoporous carbon, and graphene [9]. However, these materials are produced from non-renewable materials through high energy consumption processes, and there are certain limitations and challenges in large-scale application [22].

Activated carbon extracted from biomass and waste is suitable as a CDI electrode material because of its availability, environmentally friendly, low cost, and sustainability [23]. In addition, activated carbon from biomass has high specific surface area, high conductivity and good pore distribution [24,25]. Therefore, carbon electrodes based on renewable resources have the advantages of eco-friendliness and easy availability, and their research has important prospects. Due to the ease of availability and affordability of biomass sources and the low-energy of CDI, it makes it a strong prospect for rural desalination particularly due to activated carbon from fossil feedstocks being expensive and energy-intensive. Another strong prospect for CDI electrode materials is industrial wastewater, where specific biomass source materials could be used for selective metal ion removal.

From the analysis data from the Web of Science, there are a lot of studies on CDI electrode materials, but there are still relatively few studies about using food waste/biomass derived electrodes for CDI, and the start is relatively late. Fig. 3 shows that the research has only started

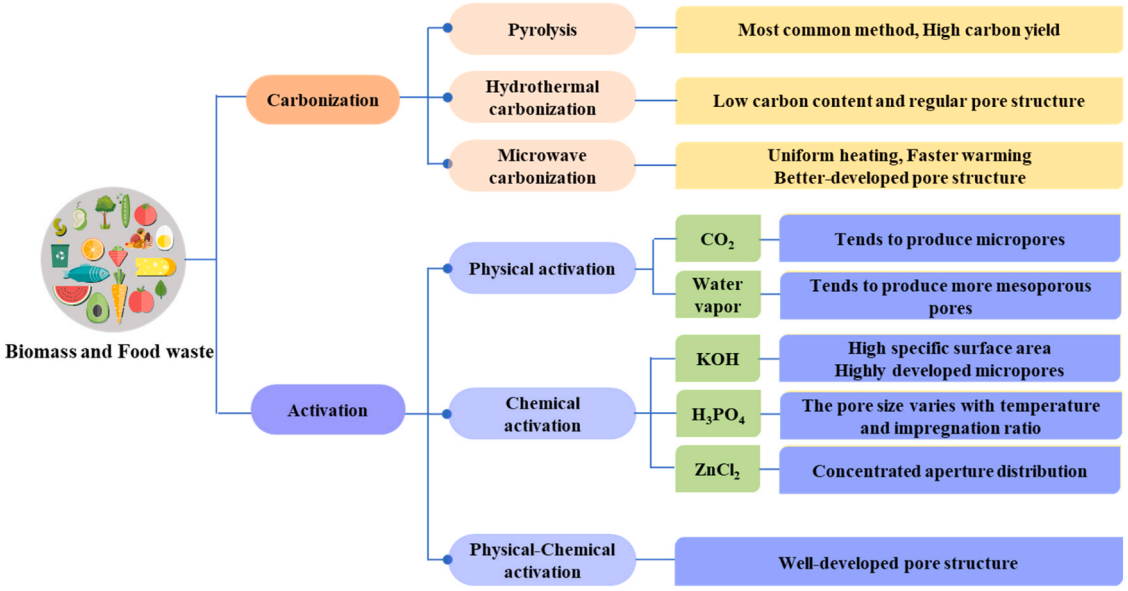

Fig. 4. Preparation methods of bio-based carbon from biomass and food waste.

in recent years and there are few relevant publications. In this paper, the preparation of CDI electrodes using biomass and food waste as carbon sources and its application progress are introduced.

2. Preparation methods of bio-based carbon from biomass and food waste

Society is currently facing the dual challenges of resource depletion and waste accumulation, with increasing efforts to reduce the use of fossil fuels and replace them with green and sustainable alternatives, thereby reducing environmental, economic and social [26]. On the other hand, agriculture, food, and industry produce a large number of by-products that are simply discarded as biological waste, which can lead to potential environmental problems [27]. There is growing recognition that the challenges of resource depletion, waste management, and loss of valuable wastes are all solvable and that more efficient use of biowastes will contribute to sustainable development [28]. Activated carbon extracted from biomass is suitable as a CDI electrode material because of its availability, environmentally friendly, low cost, and sustainability [23].

The preparation of biomass activated carbon generally includes two processes: carbonization and activation. Carbonization is a process of producing biochar with relatively stable structure at high temperature under anaerobic or oxygen-limited conditions [29,30]. The pore structure of biochar prepared by carbonization process is not developed, and only the basic and partially developed pore structure has low adsorption capacity and specific surface area, which needs to be expanded by activation process. The activation stage plays a very important role in changing the microstructure characteristics of carbon and finally making it an active carbon with excellent properties [30,31]. Fig. 4 shows the main methods and processes for preparing bio-based carbon.

2.1. Carbonization

The carbonization process is essentially the pyrolysis and polycondensation of organic matter.[30] At high temperature, organic matter is decomposed, carbon atoms continue to cyclize and aromatize, so that hydrogen, oxygen, nitrogen and other elements continue to decrease, and carbon elements continue to enrich [31,32]. The carbonization methods can be divided into pyrolysis carbonization, hydrothermal carbonization and microwave carbonization [22,26,29]. In the carbonization process, the factors that have great influence on the biochar mainly include carbonization temperature, heating rate and holding time. Generally, the porosity and specific surface area of the biochar obtained from carbonization are low.

2.1.1. Pyrolysis

As the most stable and reliable preparation method of biochar, pyrolysis is the most used. Pyrolysis refers to the method of placing raw materials under high temperature conditions under oxygen-free or oxygen-deficient conditions to make them undergo cracking reaction to obtain biochar, mainly including rapid pyrolysis and slow pyrolysis [22, 33]. The biochar produced by slow pyrolysis is mainly composed of graphite layer, and under high temperature conditions, the alkyl oxygen and alkyl carbon on the surface will be further converted into aromatic carbon. Although the process of preparing biochar by slow thermal decomposition method is slow, the yield of biochar is high [34]. Among them, carbonization temperature is one of the key factors affecting the physical and chemical characteristics of biochar, thereby affecting the application ability of biochar.

2.1.2. Hydrothermal carbonization

Hydrothermal carbonization method refers to the preparation of biochar from biomass raw materials through a series of reactions such as hydrolysis, dehydration condensation, decarboxylation, aromatization and polymerization under a certain temperature and pressure, with saturated water as the medium and under the action of catalysts. These reactions involved in the hydrothermal carbonization process of biomass are usually concurrent under different reaction paths and are not chained [30,34–36]. The specific surface area of biochar obtained by this method is small, and nanospheres, nanotubes, nanofiber configurations, porous and microporous structures can be formed. Compared with the thermal decomposition method, the hydrothermal carbonization temperature is milder, the elemental composition of the obtained biochar does not change much compared with the raw material, and the carbon and oxygen content account for a large proportion [29].

2.1.3. Microwave carbonization

The microwave decomposition method uses molecular polarization and ionic conduction to make the molecules inside the material move at extreme speed, resulting in the material surface. The layers gradually break up and eventually carbonize to form biochar. Compared with conventional pyrolysis, its advantages are simple equipment, easy operation, low energy, heating speed, high yield and a wider

Table 1
Comparison of pyrolysis and hydrothermal carbonization characteristics and the physical and chemical properties of the obtained biochar.

Production technologies of biochar	Reaction temperature /℃	Physical properties of biochar			Chemical properties of biochar		
		Carbon yield	SSA	Pore structure	Degree of aromatization	Surface functional groups	Thermo-stability
Pyrolysis	200–900	Low	Big	Rich	Low	Poor	High
Hydrothermal carbonization	180–300	High	Low	Poor	High	Rich	Low

SSA: specific surface area

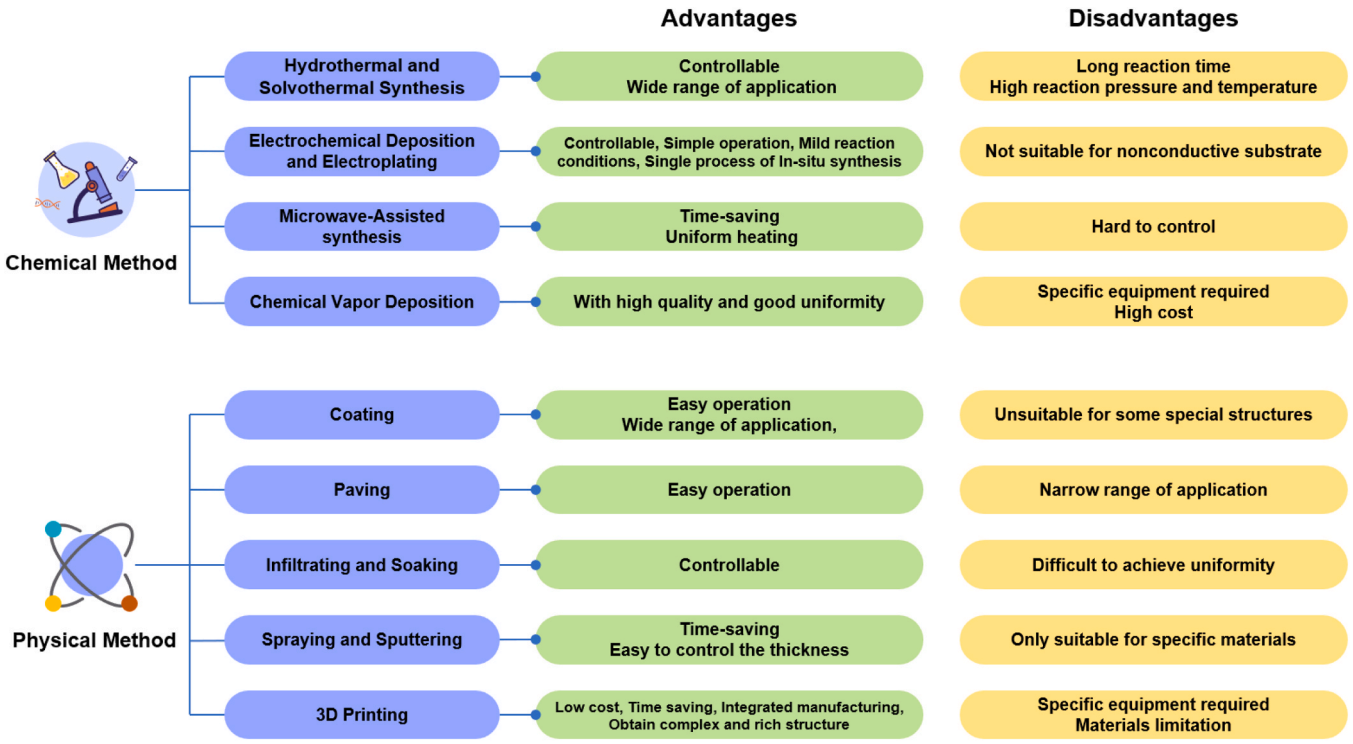

Fig. 5. Comparison of different preparation methods.

distribution of micropores and mesoporous pores [26,37].

The characteristics of thermal decomposition method and hydrothermal carbonization method of biochar and the physical and chemical properties of the obtained biochar are compared in Table 1.

2.2. Activation

Biochar obtained directly from raw materials by various means has such problems as small specific surface area, single pore structure, insufficient surface functional group resulting in poor adsorption capacity for specific pollutants. Raw materials are often required to be pretreated or modified to improve the specific surface area of biochar and enrich the pore structure distribution of biochar to remove specific contaminants [30]. Most activation methods of biochar are physical and chemical. Physical activation has the advantages of no adding impurities, low cost, easy control. Chemical activation is usually the method of adding chemicals to the raw material to change the chemical properties of the surface of biochar, which mainly includes acid-base modification, oxidizer modification and reducing agent modification [30,31,38].

2.2.1. Physical activation

Physical activation method, also known as gas activation method, refers to the carbonization of raw materials under high temperature conditions, and then oxidation reaction with carbonized raw materials with oxidizing gases such as water vapor and air to form a porous structure. The commonly used gases are mainly water vapor and carbon dioxide [24,31].

2.2.2. Chemical activation

Chemical activation method is generally a method of adding a chemical agent as an activator to the raw material and heating it in an inert gas atmosphere according to a certain concentration and impregnation ratio and simultaneously activating and carbonizing. According to the different activators, the chemical activation method can be mainly divided into $ZnCl_2$ activation method, H_3PO_4 activation method, KOH activation method, etc. The chemical activation method mainly has the advantages of low temperature, short activation time, easy control of the reaction process, etc., and is the main preparation method of high-performance activated carbon [30,32,39].

2.2.3. Physical-chemical activation

Physical-chemical activation is an activation method that combines the two methods of physical activation and chemical activation. The raw material is first impregnated with a chemical activator and then physically activated by an inert gas. The application of this method can prepare biomass activated carbon with special fine pore distribution, and the number of fine pores can be greatly increased [24,31,39,40].

3. Methods of bio-based carbon electrode fabrication

The basic method for preparing electrodes is physical methods, such

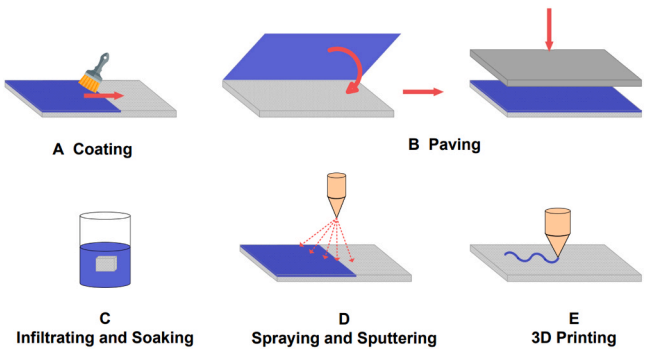

Fig. 6. The diagram of the physical preparation method of electrode.

as coating, paving, spraying or sputtering, soaking or infiltrating. Soaking or infiltrating is a promising method, and these physical methods have been widely used in industrial production and laboratory scale because of their simple operation and high-cost effectiveness. However, for some special structures and materials, simple operation may not be suitable. Therefore, chemical methods are also widely used. It is also common to make electrodes using a combination of two or more methods [41,42]. For example, chemical methods are used to obtain the active substance, while physical methods are used to attach the active substance to the substrate. New materials can be synthesized, and new structures designed through chemical reactions. Through physical methods, different materials can be compounded, and the interface combination provides an improvement of the entire electrode [42–44]. These different technologies give the electrode variety and flexibility, allowing more materials to be applied and higher energy densities to be achieved. The comparison of different preparation methods is shown in Fig. 5, and the diagram of the physical preparation method is shown in Fig. 6.

4. Application of electrode derived from biomass and food waste in CDI

The electrode derived from biomass and food waste has been widely used in CDI, such as for wastewater treatment, removal heavy metal ion, and desalination [40,45]. These substances may be less expensive and more environmentally friendly than conventional electrode materials like carbon or metal oxides. Examples of biomass and food waste materials that have been utilized as CDI electrodes include: fruit and vegetable waste [32], grape pomace [46], banana peels [47], wood waste [48], agricultural waste including maize stalks and rice straw [49, 50], microbial biofilms [51], wood or coconut shells [52–54], food waste materials like potato peel and chicken feather [55], tea leaves and tea waste [56,57], coffee grounds [58], waste cooking oil, palm wastes, physic nut wastes, and fish waste [37,59–63]. All these have been used to create CDI electrodes. These substances include a lot of organic content and are easily transformed into activated carbon, which works well in CDI systems [37,58,59,64–66].[67–72] Table 2 shows the application of different types of electrodes made from biomass or food waste in CDI.

Table 2 indicated several materials and methods that show high promise for CDI application. High specific capacitance was shown to be often positively correlated with enhanced absorption capacitance; a study that used peanut shell waste to desalinate wastewater showed a 99.9 % Cr^{6+} removal with a specific capacitive of 610 F/g [73]. Another study removing Cr^{6+} from wastewater using corncob waste had a 91.6 % removal with a high specific capacitive of 452 F/g [74].

A CDI study using carbon nanosheet derived from lotus leaf had a SSA of 4482 m^2/g and resulted in a high absorption capacitance of 65 mg/g [75]. Additionally, a study that examined the removal of metal ions by capacitive deionization with straw waste indicated a 91.5–100 % heavy metal removal with a high SSA of 2695 m^2/g [76]. However, despite these two studies showing high values of both SSA and absorption capacitive there are outliers which show high levels of absorption capacitance for low values of specific surface area, for example a desalination study that had a low SSA of 304 m^2/g but still was able to produce a high ion adsorption of 68.4 mg/g [77].

The most promising studies showed high values of SSA, specific capacitance and absorption capacitance, where lotus leaf, straw waste and peanut shell derived electrodes showed to be promising candidates [73,75,76].

Fig. 7 also indicates the effect that different carbonization and chemical activation processing methods have on specific surface area found from Table 2. It can be clearly seen that KOH is the most common activation agent for food waste or biomass derived electrodes, however, has a large range of producible specific surface areas. Despite $ZnCl_2$ showing promise as an activating agent in a prior desalination study for electrospun carbon nanofiber electrode [78], to the author's knowledge there are only two studies that have used $ZnCl_2$ as an activating agent for food waste or biomass derived electrodes.

Pyrolysis is the most common carbonization method, but it typically yields the lowest average specific surface area, despite occasionally reaching high peak values. In contrast, microwave and microwave-assisted hydrothermal methods tend to produce higher average specific surface areas, though significantly fewer studies have been conducted on these techniques.

5. Conclusion

The choice of electrode material is the key to CDI technology, which directly determines the efficiency and capability of CDI. Therefore, choosing the right material is crucial to achieving high battery performance. There is a global demand to mitigate and reduce discarded biomass and food waste. Therefore, the potential of biochar extraction from biomass and food waste is unquestionable, as it can simultaneously solve and mitigate global challenges such as resource depletion, waste accumulation and environmental pollution.

The applications of biochar from biomass and food waste as advanced electrode materials are also reviewed. The present situation of biomass and food waste in the world and the technology and method of biochar conversion and electrode preparation by physical, chemical and other methods are introduced. It is found that bio-based activated carbon extracted from biomass and food waste has the characteristics of "high specific surface area", high electrical conductivity and good pore distribution. Based on biological carbon electrode has the advantages of low cost, availability, environmental friendliness and sustainability, its research has important prospects and significance.

The research on the application of bio-based carbon electrode in CDI has only begun in recent years. Some key problems still limit the practical application and development of bio-based carbon electrode in CDI. Limitations are mainly shown in the following aspects: (1) Diverse preparation methods of biobased carbon, complex structure and properties, the selective adsorption mechanism of ions needs to be further studied. (2) Low energy density, insufficient specific capacitance, and poor stability. (3) Lack of research on electrochemical performance and long-term economic benefits. To address the above challenges, future research on bio-based carbon materials can focus on the following aspects:(1) Efficient removal of specific ions from complex systems through in-depth exploration of the selective adsorption mechanism of ions. (2) Synthesize bio-based carbon with excellent structure, abundant functional groups, ideal pore size distribution and stability. (3) Economic and environmental feasibility study of bio-based carbon application in CDI.

CRediT authorship contribution statement

Ruo Ruijie: Writing – review & editing, Writing – original draft.

Table 2
Application of different types of electrodes made from biomass or food waste in CDI.

Type	Year	Resource	Fields of application in CDI	Preparation methods of bio-based electrode	Structure	Type of operation	SSA $m^2.g^{-1}$	Specific capacitive F/g	Scan rate mV/s	Applied Voltage V	Feed Concentration	Salt removal percentage (%) or Electroabsorption capacitive(mg/g)	Ref.
Plant-based	2015	Cotton	Desalination	Pyrolysis, NH_3 treatment, annealing	Three-dimensional inter-connected pore structure	Batch	2680	109.9	10	1.2	500	16.1 mg/g	[79]
	2017	Lentinus edodes	Desalination	Hydrothermal method and $ZnCl_2$ activation	-	Batch	-	247.6	1	1.2	500 ppm NaCl	12.9 mg/g	[80]
	2017	Soybean shell	Desalination	Pyrolysis and $KHCO_3$ activation in N_2	Mesoporous structure	Batch	1036.2	215.3	-	1.2	40 mg/L NaCl	15.5 mg/g	[81]
	2017	Limonia acidissima shell	Wastewater treatment	Chemical and thermal modification	Highly nanoporous and microporous structure	Batch	-	-	–	1.2	10	Cr^{6+}: 92.2 % F^-: 89.23 %	[82]
	2017	Corncob	Wastewater treatment	Hydrothermal carbonization and KOH activation	Hierarchal macroporous and mesoporous structure	Batch	952	452	10	1	30	Cr^{6+}: 91.58 %	[74]
	2018	Loofa sponge	Desalination	Pyrolysis and chemical activation	Hierarchical pore structure	Batch	1819	93	-	5	10 mM NaCl	22.5 mg/g	[83]
	2019	Pine pollen	Desalination	High temperature carbonization, activation with NH_4Cl	Mesoporous structure	Batch	1016	94.16	10	2	500μS/cm NaCl	14.93 mg/g	[84]
	2019	Tamarind shell	Desalination	Pyrolysis, KOH activation and N-doped	Hierarchical pore	Batch	410	174.5	10	1.2	600 mg/L NaCl	18.8 mg/g	[85]
	2019	Date seeds	Desalination	Pyrolysis and KOH activation	Mesoporous and uniformly distributed pore structure	Batch	1020.85	400	10	1.2	250 mg/L NaCl	22.2 mg/g	[49]
	2019	Peanut shell	Wastewater treatment	Pyrolysis and synthesis	Highly mesoporous structure	Batch	680	610	10	1.2	50	Cr^{6+}:99.9 %	[73]
	2020	Almond shell	Desalination	Pyrolysis and CO_2 activation	-	Batch	452.2	-	-	1.2	500 mg/L NaCl	19.2 mg/g	[86]
	2020	Bamboo	Desalination	Acidification, chemical coprecipitated method, and synthesis	Hierarchical porous structure and MnO_2 nanoparticles	Batch	1747	158.2	10	1.2	105 mg/L NaCl	10.3 mg/g	[87]
	2020	Coconut shell	Desalination	Carbonization, KOH activation, indirect co-precipitation (MnO_2)	-	Batch	304	410	5	1.2	1000 mg/L NaCl	83.4 %, 68.4 mg/g	[77]
	2020	Coconut shell	Desalination	-	Disordered amorphous composite structure	Batch	630	90.2	20	1	200 ppm NaCl	14.1 mg/g	[88]
	2020	Date palm tree wastes	Desalination	Chemical activation, hydrothermal	Tube-like cavities and octahedrally-shaped nanostructures	Batch	1224	259	10	1.2	600 mg/L NaCl	17.8 mg/g	[89]

(*continued on next page*)

Table 2 (*continued*)

Type	Year	Resource	Fields of application in CDI	Preparation methods of bio-based electrode	Structure	Type of operation	SSA $m^2.g^{-1}$	Specific capacitive F/g	Scan rate mV/s	Applied Voltage V	Feed Concentration	Salt removal percentage (%) or Electroabsorption capacitive(mg/g)	Ref.
				method and synthesis									
	2020	Lotus leaf	Desalination	Carbonization and KOH activation	Porous carbon nanosheets	Batch	4482	289	-	1.6	2000 mg/L NaCl	65 mg/g	[75]
	2020	Peanut Shell	Desalination	Hydrothermal method, KOH activation and synthesis	Rough surfaces, cavities	Batch	1013.5	113	10	1.5	1000 mg/L NaCl	8.98 mg/g	[90]
	2020	Pinecone	Desalination	H_3PO_4 activation, P-doped	Graphization	Batch	1176	-	10	1.2	1000 mg/L NaCl	14.62 mg/g	[91]
	2020	Sugarcane bagasse	Water treatment	Pyrolysis, KOH activation, incipient-wetness impregnation, further pyrolysis in N_2 atmosphere	Hierarchical porous structure	-	1692.6	185.6	100	1.2	15 mg/L	20.9 mg/g	[92]
	2020	Watermelon	Desalination	Pyrolysis, H_3PO_4 activation, hydrothermal technique, incorporation of $MnFe_2O_4$ nanoparticles	-	Batch	483	425	10	1.2	250 mg/L NaCl	29.7 mg/g	[93]
	2020	Sugarcane bagasse	Desalination	Microwave-aided Carbonization and CO_2 activation	Hierarchical porous structure	Batch	764	123	5	1.2	10 mM NaCl	11.4 mg/g	[94]
	2020	Rice husk	Desalination, Softening, Water treatment	Hard template method, alkaline leaching, and chemical activation	Hierarchical porous	Single-pass	1839	120.5	5	1.2	20 mM NaCl 2 mM NH_4Cl 5 mM $MgCl_2$ 0.1 mM $CuCl_2$	8.11 mg/g NH_4^+:1.54 mg/g Mg^{2+}:1.53 mg/g Cu^{2+}: 0.52 mg/g	[95]
	2020	Rice husk	Wastewater treatment	Chemical and thermal modification	Microporous structure	Batch	-	-	-	1.2	10	Cr^{6+}: 85 %	[96]
	2020	Red oak	Wastewater treatment	Carbonization and KOH activation	Graphitized structure	Batch	303.59	20	-	1.8	200	Cr^{3+}: 100 % Cl^-: 86.7 %	[97]
	2020	Straw waste	Wastewater treatment	Carbonization and synthesis	Sheet-like and porous structure	Batch	2695	221.9	1	1.2	100	Cd^{2+} 91.5 % Ni^{2+} 97.0 % Cu^{2+} 100 %	[76]
	2020	Date seed waste	Wastewater treatment	Pyrolysis and KOH activation	Porous interconnected carbon walls in honeycomb-like structure	Single-step	-	250	10	1.2	120	Cr^{6+}: 38.6 mg/g	[98]

(*continued on next page*)

Table 2 (*continued*)

Type	Year	Resource	Fields of application in CDI	Preparation methods of bio-based electrode	Structure	Type of operation	SSA $m^2.g^{-1}$	Specific capacitive F/g	Scan rate mV/s	Applied Voltage V	Feed Concentration	Salt removal percentage (%) or Electroabsorption capacitive(mg/g)	Ref.
	2021	Chestnut shells	Wastewater treatment	Carbonization and chemical activation	Hierarchical porous structure with macroporous and mesoporous features	Batch	429	131	10	1	30	Cr^{6+}:90.5 %	[99]
	2021	Date Palm leaflets	Water and wastewater treatment	Carbonization and NaOH activation	Nanoscale highly porous structures mixed with cylindrical-like cavities structure	Batch	604.3	23.34	1	1.8	100 ppm NaCl 10 ppm Methylene blue	5.38 mg/g Methylene blue:85 %	[100]
	2021	Waste cattail	Water and wastewater treatment	Pyrolysis	Multichannel and porous framework higher degree of aromatic structure	Batch	733.62	86.5	5	1.2	20	F^-:91.98 %	[25]
	2022	Chestnut shell	Wastewater treatment	Carbonization and modified with aryl diazonium salt	Hierarchical porous structure	Batch	2194.82	53.91	1	1.2	30	Sr^{2+}:33.11 mg/g	[101]
	2022	Pomelo peel	Wastewater treatment	Carbonization and KOH activation	Hierarchical porous structure	Batch	546.3	109.8	1	0.9	100	U^{6+}:237.9 mg/g	[102]
	2022	Walnut shell	Desalination	Hydrothermal carbonization and KOH/ $ZnCl_2$/$K_2C_2O_4$ activation	Complex hierarchical porous structure	-	1600.34 1377.36 99.0 876.62 114.3	106.2	1		50 mg/L MgCl2	17.1 mg/g 14.5 mg/g 12.8 mg/g	[103]
	2023	Sargassum	Wastewater treatment	Microwave synergistic nitrogen/ phosphorus doping	Internally interconnected hierarchical porous structure	-	1367.6	531	-	1	50 mg/L	Cu^{2+}: 56.16 mg/g	[104]
	2023	Badam tree leaf	Wastewater treatment	Alkaline treatment and microwave-assisted hydrothermal method	Uniformly interconnected micro-mesoporous structure	-	1075	~210	5	1.4	150 mg/L	45.1 mg/g	[105]
	2023	Coconut-shell	Wastewater treatment	Carbonization and KOH activation	Microporous structure	Batch	581	133.7	-	1.2	200 pm $CuSO_4$ 200 ppm $ZnSO_4$	Cu^{2+} 7.31 mg/g Zn^{2+} 12.55 mg/g	[106]
Food waste	2017	Tea waste	Wastewater treatment	Chemical and thermal modification	Highly microporous structure	Batch	-	-	-	1.2	10	Cr^{6+}: 88.5 % F^-: 85.20 %	[57]
	2018	Citrus peel	Desalination	Synthesized by hydrothermal reaction and carbonization	Abundant micropore	Batch	323	120	1	1.5	500 mg/L NaCl	16 mg/g	[32]
	2019	Jackfruit peels	Desalination	Carbonization, KOH activation	-	Batch	1955	307	5	2	30 mg/L NaCl	1.18 mg/g	[107]
	2019	Sugarcane bagasse	Desalination	Microwave carbonization and KOH activation in N_2/CO_2	Hierarchical pore structure	Batch	1019	208	5	1.2	292 NaCl	28.9 mg/g	[94]

(*continued on next page*)

Table 2 (*continued*)

Type	Year	Resource	Fields of application in CDI	Preparation methods of bio-based electrode	Structure	Type of operation	SSA $m^2.g^{-1}$	Specific capacitive F/g	Scan rate mV/s	Applied Voltage V	Feed Concentration	Salt removal percentage (%) or Electroabsorption capacitive(mg/g)	Ref.
	2020	Jackfruit peels	Water and wastewater treatment	Carbonization and KOH activation	Micro/mesoporous structure	Batch	1350	298	5	2	3.11	F^-: 0.13 mg/g Ca^{2+}:0.59 mg/g Mg^{2+}:0.50 mg/g	[108]
	2020	Egg whites	Desalination	carbonization, KOH activation and N-doped	Micro-mesopore structure	Batch	3277.96	136.61	100	1.2	500 mg/L NaCl	26.67 mg/g	[109]
	2021	Pomegranate peel	Wastewater treatment	Pyrolysis and KOH activation	Highly mesoporous structure	Batch	640	180	50	1.2	1000 mg/L NaCl	36 mg/g	[19]
	2022	Banana peel waste	Wastewater treatment	Hydrothermal method with Fe_3O_4	Crystalline cubic face-centered structure	Batch	827	285	10	1.2	10	Pb^{2+}:90 %	[110]
Animal-based	2019	Chicken feather	Wastewater treatment	Pyrolysis and KOH activation	Flake-like and graphitic structure	Batch	2481	-	-	1.2	100 mg/L Pb $(NO_3)_2$	Pb^{2+}:81 % or 4.1 mg/g	[55]
	2020	Leather wastes	Desalination	-	-	Batch	2523	132.22	2	1.2	500 mg/L NaCl	20.92 mg/g	[111]

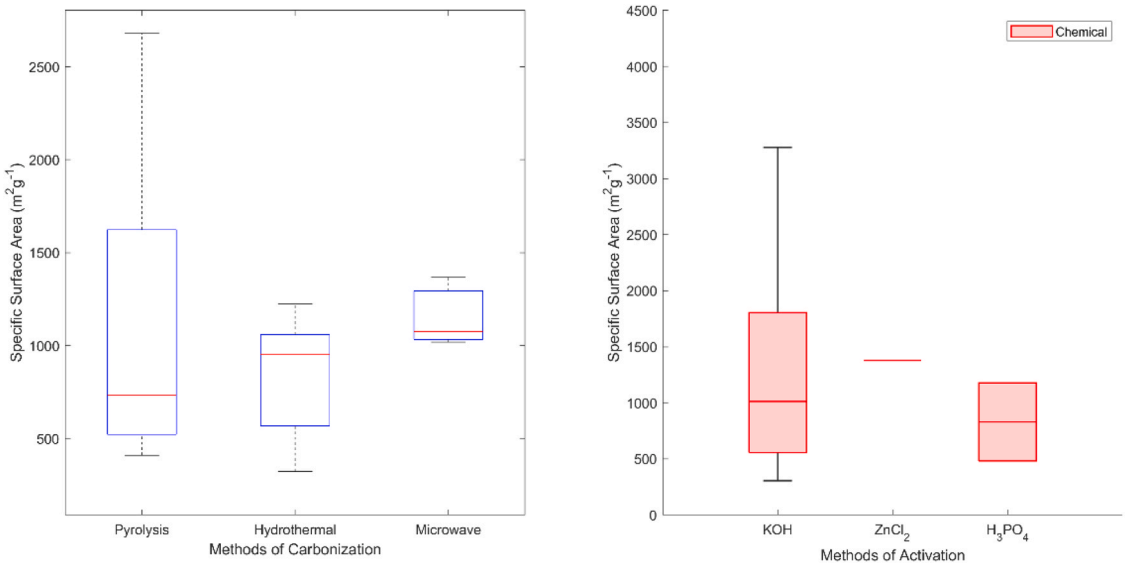

Fig. 7. Specific surface area for different methods of carbonization and activation.

Sarper Sarp: Writing – review & editing. **Machiwenyika Kevin:** Writing – review & editing, Writing – original draft. **Waye Zhang:** Writing – review & editing, Writing – original draft. **Matthew Bedding-Tyrrell:** Writing – review & 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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Data Availability

No data was used for the research described in the article.

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