



Recent advances: Biomass-derived porous carbon materials

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ABSTRACT

Biomass-derived porous carbon materials are a new type of popular environmentally friendly materials that have attracted researchers worldwide attention due to their well-developed and easy control pore structure, high specific surface area, higher graphitization degree, etc. Although there have been many critical reviews and summaries on biomass-derived porous carbon materials, improvements, revisions, and additions are still needed. This paper critically reviews the current knowledge and summarizes the recent advances in biomass-derived activated carbon and carbon aerogels that considers porous carbon materials. In addition, the application of biomass-derived porous carbon materials as electrode materials for supercapacitors and anode materials for lithium-ion and potassium-ion batteries are reviewed. Moreover, biomass-derived carbon aerogels are shortly discussed as absorbent materials for spilled oils and organic solvent recovery. Finally, the conclusions and prospects of biomass-derived porous carbon materials are discussed.

1. Introduction

With the world population growth and the intensive development of energy-intensive technologies, the level of energy consumption is increasing, a significant part of which is produced by burning organic fossil fuels. This leads to the depletion of non-renewable energy resources and the release of a huge number of pollutants into the atmosphere, which has a detrimental effect on the environment. Modern technologies to produce electricity using renewable sources (water, sun, wind, gravity, etc.) contribute to ensuring environmental and energy security in a modern technological society. However, the main disadvantage of these branches of the electric power industry is the lack of effective technologies that allow the accumulation and storage of manufactured goods on an industrial scale. Industrial technologies of accumulation and storage allow to accumulation of electricity when consumption is lower than its production, and vice versa, to supply electricity when consumption is higher than its production, which will allow the use of generated electricity without loss. This is most relevant in the production of electricity using solar and wind energy since their performance directly depends on the length of daylight hours and weather conditions. The paper (Erdem, 2021) discussed in detail the possibilities of Power-to-X (P2X) technology to solve the problems of

decarbonization and emphasized the important role of the need to develop new systems for safe and efficient storage and use of excess energy generated by solar and wind energy to increase the efficiency of Power-to-X technology (P2X). A similar direction is consecrated in the review (Fagiolarini et al., 2022), which is devoted to a new class of hybrid devices for collecting and storing energy that combines solar cells and electrochemical energy storage devices. At the present stage, compared with batteries, supercapacitors are more promising devices for storing energy on an industrial scale.

The paper (Najib and Erdem, 2019) presented the current state of manufacturing technologies for almost all existing types of supercapacitors and discussed in detail the relationship of their specific capacitance with their design, the structural characteristics of the materials used in the electrodes, and the electrochemical properties of electrolytes and carried out a comparative analysis of their advantages and disadvantages.

According to the mechanism of energy storage, supercapacitors are divided into three main types electric double-layer supercapacitors (Belhachemi et al., 2000), pseudo-capacitors (Qu et al., 2022; Hu et al., 2021; Eskandari et al., 2020) and hybrid supercapacitors (H. D. Wang et al., 2022; Zhang et al., 2021), which differ in the mechanism of electric energy storage. Compared to batteries, supercapacitors have

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some advantages. The first is the charging speed. The widely used lithium batteries do not carry large currents. When charging with a large current, they overheat, and quickly degrade, which often leads to an explosion of lithium batteries (Wang et al., 2019; Chombo and Laoonual, 2020; Zhao et al., 2021, 2022). Because of this, it is impossible to charge the battery in less than an hour. A distinctive feature of supercapacitors is that they can charge much faster (Hussain et al., 2021; Xie et al., 2021; Tan et al., 2022). The second advantage is the long service life. Lithium cells show a service life of about 1000 charge/discharge cycles without significant loss of capacity. A supercapacitor can survive 10, 100 thousand, and even a million cycles without consequences. The third advantage is that supercapacitors have a huge operating temperature range. Currently, supercapacitors are being sold on the market that can operate at temperatures from -40°C to $+85^{\circ}\text{C}$ (Xu et al., 2019; Sun et al., 2022). Moreover, a significant advantage is that supercapacitors are not toxic, chemically inactive, therefore they are environmentally safer. However, the low energy density is one weakness that limits the widespread in supercapacitors (Bai et al., 2019; Wang et al., 2020). Hence, intensive research has been carried out to find new effective electrode materials and new technologies for the manufacture of supercapacitors.

Porous carbon, carbon nanotubes, graphene, carbon fibers, carbon whiskers, and their composites are widespread electrode materials (Sun et al., 2022; Daulbayev et al., 2022, 2021). One of the promising electrode materials for supercapacitors and anode and cathode materials for alkali metal ion-batteries is porous carbon materials. They can be taken from biomass including renewable crops which are regarded as an environment-friendly precursor which brings less pollution to the atmosphere (Fig. 1a). Moreover, these materials are natural abundance, regeneration, inexpensiveness, availability in large amounts and can be prepared by a simple method. Common porous carbon materials mainly include activated carbon materials (Teo et al., 2016; Liu et al., 2019; Mai et al., 2019), carbon aerogels (Vazhayal et al., 2020; Chen et al., 2020; Yang et al., 2021) and others (Chen et al., 2017; Asadi et al., 2021). They are porous materials with a well-developed and easy control pore structure, a high specific surface area (SSA), and a high adsorption capacity (Gu and Yushin, 2014; Mai et al., 2019). Previous reports have demonstrated that various renewable and eco-friendly biomass-derived carbon materials including peanut shells (Zhan et al., 2021), eggfruit-derived (Zou et al., 2022), sorghum seeds (Feng et al., 2021), eggplant (Li et al., 2022), rice husk (RH) (Liang et al., 2022), (Li et al., 2021), rape pollen (J. J. Zhao et al., 2022), grape stem (He et al., 2022), bagasse (Deng et al., 2021), soybean (D. D. Wang et al., 2022), etc. have been investigated for obtaining high electric capacities and excellent electrochemical properties when applied in supercapacitor electrode (Zhan et al., 2021; Zou et al., 2022; Feng et al., 2021; Li et al., 2022), in lithium-ion (Liang et al., 2022; J. J. Zhao et al., 2022; He et al., 2022) and KIBs (Deng et al., 2021; D. D. Wang et al., 2022) (Fig. 1b).

Literature analysis indicates that last years, an active search for high-

performance electrode and anode materials for applications in the field of energy storage. Most of the used electrode and anode materials relate to biomass-derived porous carbon, which, due to its excellent physicochemical and electrochemical properties, will solve the energy storage problem and the problem associated with finding alternative and eco-friendly methods of its production. From this point of view, a comprehensive analysis of research in the field of energy storage using biomass-derived nanoporous carbon materials is required. In this regard, the manuscript considered the biomass-derived porous carbon materials such as activated carbon and carbon aerogels, and their morphological, structural, physicochemical, and electrochemical properties, as well as prospects for their use as electrode and anode materials in the field of supercapacitors and alkali metal ion-batteries.

2. Porous carbon materials

2.1. Activated carbon

Activated carbon is a porous carbon material that contains macro-, meso-, and micropores and has a high SSA. Activated carbon can be obtained from almost any carbon-containing material of organic origin, but the main carbon source for its production on an industrial scale are charcoal, coal and petroleum coke, rice husks (RHs), coconut shells, and oil palm empty fruit bunches (EFB), wood, nut shells and various plant wastes. In Table 1 activated carbon from different biomass precursors, their SSA and application area are collected. The activated carbon production technology includes two successive stages of carbonization and activation. The carbonization process is a heat treatment of feedstock

Table 1
Comparison of S_{BET} of activated carbon from different biomass precursors.

Raw material	SSA, m^2/g	Application	Ref.
RH	2696	Supercapacitor electrode	(Teo et al., 2016)
RH	2804–3263	Supercapacitor	(Liu et al., 2019)
RH	1583	Lithium-sulfur (Li-S) battery	(Mai et al., 2019)
RH	2176	Lithium-ion batteries (LIBs)	(Yu et al., 2018)
RH	3292	Electrode materials for supercapacitor	(Yeleuov et al., 2020)
Coconut shell	516	Water purification treatment	(Sujiono et al., 2022)
Coconut shell		Microbial fuel cell	(Neethu et al., 2019)
Oil palm EFB	1704	Electrodes for application in supercapacitors	(Farma et al., 2013)
Oil palm EFB	41–1571	A working electrode in symmetric hybrid supercapacitor	(Larasati et al., 2019)
Oil palm EFB	445–640	For producing electrode materials	(Rustamaji et al., 2022)

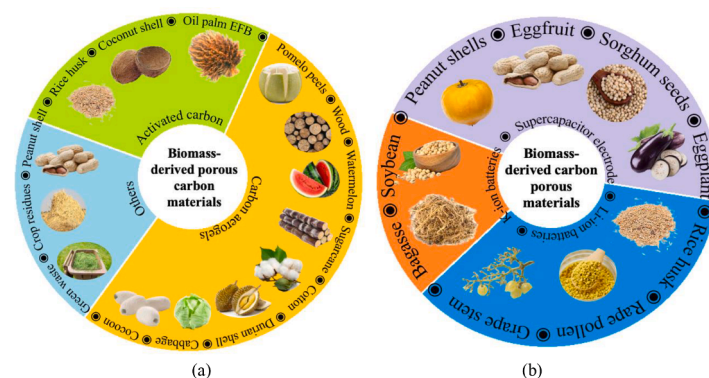


Fig. 1. Biomass-derived porous carbon materials: (a) divided by types of porous carbon materials (b) divided by application area.

without oxygen at temperatures from 450 to 650 °C. Activation is carried out at temperatures above 750 °C and two types of activation are mainly used: vapor-phase and thermochemical. The structural composition of the raw material and the conditions of their carbonization, subsequent activation, and modification of their surface have a significant impact on the structure and properties of activated carbon.

Many researchers showed the advantages of RHs which are a major by-product in the rice milling industry as the raw materials to prepare activated carbon anode and cathode materials for lithium batteries, supercapacitor electrodes, etc. Teo et al. (Teo et al., 2016) fabricated a high surface area (surface area of 2696 m²/g) activated carbon using RHs as a biomass carbon source. The obtained activated carbon applied as a supercapacitor electrode exhibited good electrochemical performance. Liu et al. (Liu et al., 2019) prepared the RH derived-activated carbons and the obtained samples exhibited a high microporous ratio, high specific area (up to 3263 m²/g), and high specific capacitance (315 F/g at 0.5 A/g). They started when the silica in rice hucks is removed, the prepared activated carbon exhibits a high mesoporous ratio and good rate capability. Mai et al. (Mai et al., 2019) developed highly porous with micro/*meso* porosity through carbonizing RH and treating them with K₂CO₃. They loaded elemental sulfur to activated carbon to prepare composite materials and then used it as a cathode material for lithium-sulfur batteries. Yu et al. (Yu et al., 2018) prepared the RH based-activated carbons (RHAC) by an effective and facile method (Fig. 2). Authors noted, NaOH, as an activator, plays a crucial role in forming the hierarchical porous structure in this method. Yeleuov et al. (Yeleuov et al., 2020) prepared a highly porous activated graphene-based carbon (AGC) by using RH as a carbon source. The obtained AGC had a very high SSA of 3292 m²/g and can be successfully used as electrode material for supercapacitors.

Sujiono et al. (Sujiono et al., 2022) fabricated a high-quality microporous activated carbon from coconut shell waste by using different activating agents. They showed the activated carbon-based on an activating agent of NaOH can potentially be applied for water purification treatment. Neethu et al. (2019) developed an affordable low-cost durable proton exchange membrane (PEM) based on activated carbon derived from coconut shell (ACCS) and natural clay for application in a microbial fuel cell.

Farma et al. (2013) prepared the highly porous binderless activated carbon electrodes from fibers of oil palm EFB for application in supercapacitors. Supercapacitors based on these electrodes exhibit excellent electrochemical performances due to the significantly increased surface area of the electrodes. Larasati et al. (2019) prepared activated nano carbon from oil palm EFB by using ZnCl₂ and CaCl₂ as a chemical activating agent during the hydrothermal process. Activated nano carbon using CaCl₂ as an activating agent is shown the capacitance of supercapacitor was 4.305 F/g. Rustamaji et al. (2022) synthesized the nitrogenated mesoporous activated carbon (N-ACU) from empty fruit

bunches of oil palm by hydrothermal carbonization and CO₂ gas activation. Thus, the ongoing research shows that renewable raw material is a promising material for obtaining porous carbon with a developed structure. Biomass attracts attention not only because it is an affordable, renewable, and cheap raw material, but also because it has a ready-made homogeneous highly developed structure, which makes it possible to obtain on its basis porous carbon material with a high SSA and uniform pore distribution, which is very important for electrode materials production.

2.2. Carbon aerogels

Last several decades, researchers interested in carbon aerogels due to their various characteristics, such as high porosity, low density, controllable surface functional groups, etc. Moreover, they are the lightest materials in the world. Since Pekala (Pekala et al., 1990) developed the first resorcinol-formaldehyde carbon aerogel, Kroto et al. (1985) discovered fullerenes, the first carbon nanomaterials, than Iijima (1991) discovered carbon nanotubes, further Geim and Novoselov (Novoselov et al., 2004) obtained graphene, 2D nanomaterials, interest to develop carbon aerogels based on carbon nanomaterials have been increased. After these discoveries, in 2007 Bryning et al. (2007) and 2009 Wang (Wang and Ellsworth, 2009) reported carbon nanotubes-based and graphene-based carbon aerogels, respectively. In 2011 Pauzauskie (Pauzauskie et al., 2011) synthesized diamond-based carbon aerogels and later a lot of research works (Kabiri et al., 2014; Sultanov et al., 2014; Zhao et al., 2018) in this area have been published. These aerogels have good mechanical characteristics (Bryning et al., 2007), but synthesis methods of these precursors are high-cost and complicated. For instance, the synthesis of graphene by CVD method, which is a widespread method, can produce graphene with high quality, but they have very low production rates. Another method, which can be used to produce graphene is mechanical exfoliation, where graphene with lower quality, but with high production rates can be obtained. Moreover, carbon nanomaterials are nonrenewable and their influence on human health has not yet been comprehensively investigated (Chen et al., 2020).

Another important type of carbon aerogels is biomass-derived carbon aerogels. This is because, unlike other types of carbon aerogels that use petroleum products as precursors, biomass-based carbon aerogels use biomass or biomass waste, so they are environmentally friendly and cost effective (Sam et al., 2020). In Table 2 carbon aerogels from different biomass precursors and their SSA and application area are collected. Wu et al. (2013) obtained carbonaceous gels, including carbonaceous hydrogels and aerogels by using watermelon as raw materials. Li et al. (2014) prepared 3D carbon aerogels by using winter melon as the carbon source through the hydrothermal and post-pyrolysis process. The obtained winter melon-based carbon aerogels are shown excellent

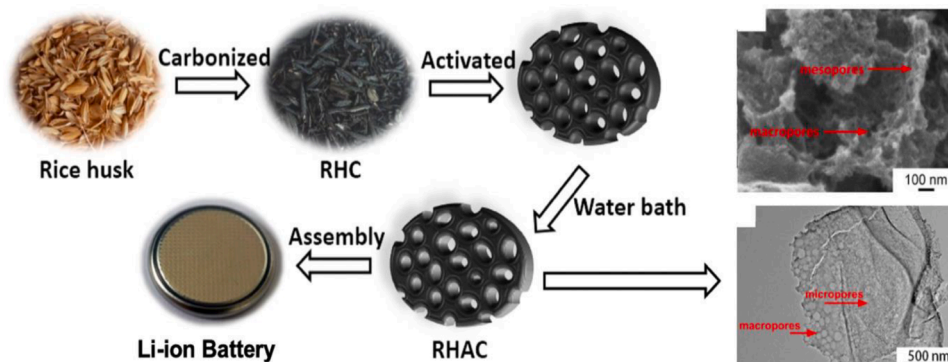


Fig. 2. Scheme of obtained RHAC anode material by a facile method and transmission electron microscopy (TEM) images of RHAC. Reprinted with permission from (Yu et al., 2018).

Table 2

Comparison of S_{BET} and application area of carbon aerogels from different biomass precursors.

Type of carbon material	Raw material	SSA, m ² /g	Application	Ref.
Carbon aerogels	Natural cotton waste	1160	Adsorbents for wastewater clean-up	(Chen et al., 2015)
Carbon aerogels	Pomelo peel	466.0–759.7	Absorbent for removal of organic pollutants/oils	(Zhu et al., 2017)
Carbon aerogels	Cabbage leaves waste	536	For supercapacitors and oil/water separation	(Cai et al., 2018)
Carbon aerogels	Durian shell	735	For removal of organic pollutants	(Wang et al., 2017)
Carbon aerogels	Cocoon	714	As efficient catalyst for the oxygen reduction reaction in alkaline medium	(Li et al., 2018)
Carbon aerogels	WTP-PVA	1384	Adsorbent, catalyst supports and in energy storage devices	(Vazhayal et al., 2020)
Carbon aerogels	Wood	1124	For pressure sensing and energy storage	(Chen et al., 2020)
Carbon aerogels	Cellulose	–	For adsorption of diesel oil	(Yang et al., 2021)
N self-doped carbon aerogel	Chitosan	1480	For high-performance supercapacitors	(E et al., 2021)
N-O-P co-doped carbon aerogel	Abundant radish	1648.91	For high-performance supercapacitors	(Zhou et al., 2021)
A N-doped carbon aerogel	Cellulose	1196	For high-performance supercapacitors	(K. J. Zhao et al., 2022)
ALC	Sugarcane	390	Sensor, energy conversion and storage, and EMI shielding	(Li et al., 2015)
HCFSs	Catkins	438	Absorbent for oils and organic solvents	(Zang et al., 2016)

hydrophobicity, and low density and they can be the absorption of oils and organic solvents 16–50 times their weight. Chen et al. (2015) fabricated carbonaceous aerogels from natural cotton waste and used them as adsorbents for wastewater clean-up. Zhu et al. (Zhu et al., 2017) prepared carbon aerogels using pomelo peels as the carbon sources via pyrolysis process at 600, 700, and 800 °C (Fig. 3a). Obtained pomelo peel-based carbon aerogels are shown that their characteristics depend on pyrolysis carbonization temperature. These aerogels had an interconnected 3D porous morphology and SSA between 466 and 759.7 m²/g. Cai et al. (2018) synthesized nitrogen-doped 3D network porous carbon aerogels by using cabbages as the raw materials through hydrothermal, freeze-drying, and carbonization processes (Fig. 3b). These aerogels had a hierarchical 3D network porous structure and shown a high-performance as electrode materials for supercapacitors, as well as high adsorption capacity and recyclability for different organic solvents and oils. Wang et al. (2017) proposed the preparation method of the carbon aerogel using waste durian shell (DSCA) as the biomass precursor and its application in the removal of organic pollutants (Fig. 3c). Li et al. (2018) converted the biomass of cocoon into a heteroatom (N, S and Fe) ternary-doped, porous carbon aerogel (HDCA) catalyst. Vazhayal et al. (2020) developed carbon aerogels using waste tissue paper (WTP) and poly(vinyl alcohol) (PVA) as a carbon source. Chen et al. (2020) proposed a facile and sustainable strategy to fabricate a wood-derived

elastic carbon aerogel with a tracheid-like texture from cellulose nanofibers (CNFs) and lignin. Yang et al. (2021) prepared carbon aerogel using the cellulose extracted from the luffa sponge for adsorption of diesel oil (Fig. 3d). Authors modified obtained carbon aerogels using trichlorosilane to enhance the adsorption capacity for diesel oil. Modified carbon aerogel had better adsorption capacity for diesel oil (49.62 g/g) than aerogel (5.2 g/g) and carbon aerogel (32.34 g/g).

Li et al. (2015) obtained an aerogel-like carbon (ALC) based on sugarcane through a hydrothermal carbonization (HTC) and post-pyrolysis process. The authors noted that the SSA of ALC, which has a subtle influence on the properties of ALC, can be finely tuned by the HTC process. Zang et al. (2016) synthesized hollow carbon fiber sponges (HCFSs) by utilizing catkins as a biomass carbon source.

Literature analysis shows carbon aerogels are mainly used as adsorbents (Vazhayal et al., 2020; Yang et al., 2021; Li et al., 2014; Chen et al., 2015; Zhu et al., 2017) for the removal of different types of organic solvents/oils, etc. due to great absorption capacity, superior hydrophobicity, good recyclability, and low cost. However, they have a limited surface area. This is one of the reasons carbon aerogels cannot use as an electrode material for high-performance supercapacitors. Recently published works (E et al., 2021; Zhou et al., 2021; K. J. Zhao et al., 2022) show introducing the more active sites of heteroatoms (N, O, P, S, etc.) to carbon aerogels can improve the SSA and it led to electrochemical properties of the biomass carbon aerogel.

3. Application of biomass-derived porous carbon materials

3.1. Electrode materials for supercapacitors

Supercapacitors are devices in which the accumulation of electrical energy occurs due to the formation of an electrical double layer at the interface between an electrolyte solution with ionic conductivity and an electrode with electronic conductivity. According to the energy storage mechanism, supercapacitors are divided into double-layer supercapacitors with ideally polarizable highly porous electrodes, hybrid supercapacitors with asymmetric electrodes, and pseudocapacitive supercapacitors, on the electrodes of which redox interactions occur during the charge/discharge process. In an electrical double layer, as in a conventional capacitor with two flat plates, the capacitance is proportional to the area of the plates and inversely proportional to the distance between them. In a double electric layer in supercapacitors, the distance between the charged surface of the electrodes and the layer of ions in the electrolyte is measured in angstroms, therefore, by increasing the specific surface of the electrodes, it is possible to create supercapacitors with a huge capacity. Thus, one of the important criteria for achieving a high capacitance of supercapacitors is the use of electrodes with a high SSA. It can distinguish the following main criteria that an electrode material intended for supercapacitors should have:

- ideal polarizability in the range of potentials limited by the potentials of the electrochemical decomposition of the solvent;
- a high surface area for high specific capacitance;
- high conductivity in the electronic component to ensure high values of power density;
- be indifferent (neutral) concerning the electrolyte solution.

These criteria are best met by porous carbon materials, which have a high SSA, stable frame structure, and mass productivity. Biomass-based carbon is promising for the creation of porous electrode materials for supercapacitors (Wang et al., 2020; Nazhipkyzy et al., 2022), especially the developments related to the utilization and use of vegetable raw materials wastes remain topical problems due to environmental and economic factors (Väisänen et al., 2016; Azat et al., 2019; Daulbayev et al., 2022). Biomass attracts attention not only because it is an affordable, renewable, and cheap raw material, but also because it has a

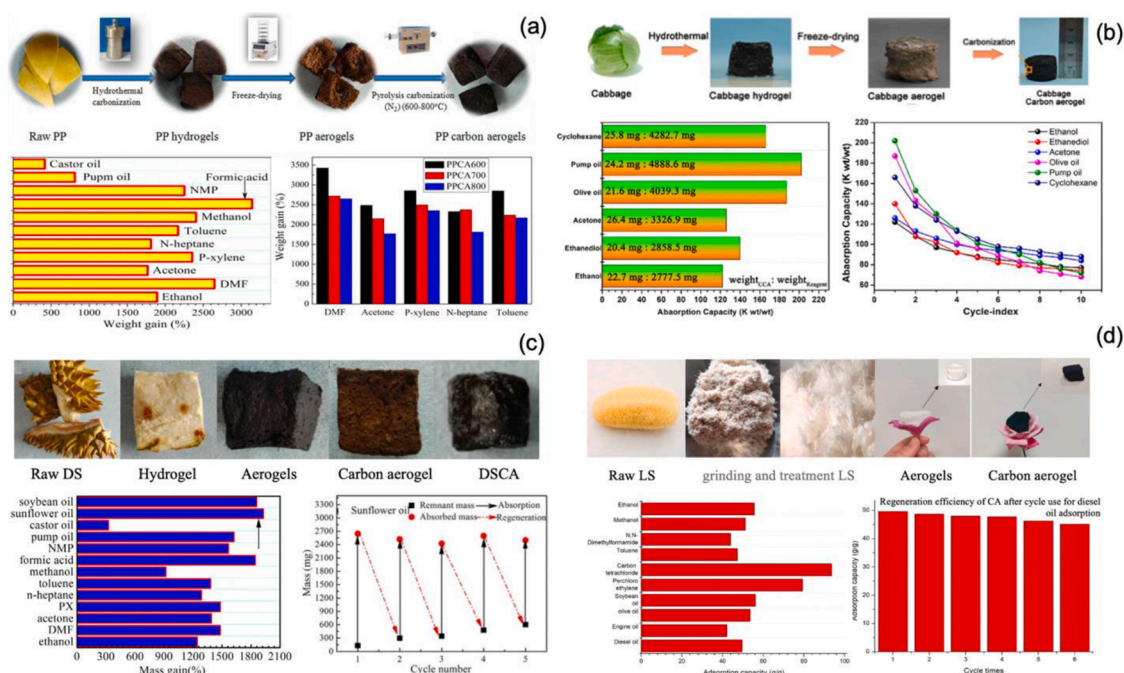


Fig. 3. Schematic illustration of the formation process of different biomass derived carbon aerogels (a) pomelo peel (PP) (Zhu et al., 2017); (b) cabbage (Cai et al., 2018); (c) durian shell (DS) (Wang et al., 2017); (d) Luffa sponge (Yang et al., 2021). Reprinted with permission from (Zhu et al., 2017; Cai et al., 2018; Wang et al., 2017; Yang et al., 2021).

highly developed homogeneous structure, which makes it possible to synthesize a porous material on its basis with a uniform distribution of pores. Hence, in recent years there has been a sharp increase in the number of research works (Zhan et al., 2021; Zou et al., 2022; Feng et al., 2021; Li et al., 2022), devoted to the production of porous carbon

materials based on plant wastes intended for supercapacitors. Recently developed and prepared porous carbon materials obtained by different biomass and their structural and electrochemical properties are collected in Table 3.

The most common raw material for supercapacitor electrode

Table 3

The structural and electrochemical properties of porous carbon materials obtained by different biomass.

Porous carbon materials	Biomass	Microstructure	SSA, m ² /g	Maximum capacitance, F/g	Stability, cycles	Maximum energy density, W h/kg	Ref.
Activated carbon	RH	Porous	2804	278 F/g at 0.5 A/g	76.6%	–	(Liu et al., 2019)
Activated graphene-based carbon	RH	A highly porous	3292	236–300 F/g at 0.5 A/g	–	–	(Yeleuov et al., 2020)
Activated carbon materials	RH	Three-dimensional	2556.8	325 F/g at 0.5 A/g	90% (10.000)	–	(Chen et al., 2021)
N-doped porous carbon	RH	Hierarchical	416	242 F/g at 0.5 A/g	–	12.04	(Xue et al., 2020)
Activated carbon	Oil palm EFB	Interconnected porous network with wrinkles	363.88–640.61	176 F/g	98.7% (5000)	–	(Rustamaji et al., 2022)
N-doped carbon aerogels	Cellulose	An interconnected honeycomb-like	1196	160 F/g	82% (3.000)	21.9	(E et al., 2021)
N–O–P co-doped porous carbon aerogel	Abundant radish	Three-dimensional	1648.91	352 F/g at 1 A/g	78.4% (10.000)	–	(Zhou et al., 2021, p.)
A porous N-self-doped porous carbon aerogel	Chitosan	Hierarchical porous	1480	1504 F/g at 1 A/g	85.9% (5.000)	33.33	(K. J. Zhao et al., 2022)
Ultra-high SSA carbon materials	–	The hierarchical porous	3710	416 F/g at 0.5 A/g	100% (10.000)	23.4	(Lin et al., 2022)
Graphitic porous biomass carbon	Dandelion	Mesoporous	780.4	309 F/g at 0.5 A/g	67% (10.000)	14.22	(Tan et al., 2022)
Porous carbons	Flower stem	Hierarchical	–	375.7 F/g at 1 A/g	92.7% (50.000)	31.3	(Wan et al., 2020)
Porous carbons incorporated with CuO nanoparticles	Orange peel	Hierarchical micro-mesoporous	2640.55	530 F/g at 1 A/g	92.5% (10.000)	11.7	(Zhan et al., 2021)
Porous carbon supported nano-Co ₃ O ₄ composite	Peanut shells	Three-dimensional network porous	87.88	781.56 F/g at 0.5 A/g	96.7% (20.000)	32.8	(Zou et al., 2022)
N ₂ O-codoped porous carbon	Eggfruit	Hierarchical	2132.1	536.7 F/g at 0.5 A/g	97.6% (15.000)	13.8	(Feng et al., 2021)
Hierarchical porous carbon materials	Sorghum seeds	Hierarchical	1947	469 F/g at 1 A/g	99.95% (20.000)	38.51	(Li et al., 2022)

material is RHs. The peculiarity of its structure is that it consists of a matrix of polymers and a reinforcing silica phase, i.e., it is a ready-made natural composite for creating a nanoporous material that will have a hierarchical microstructure for the transport of electrolyte ions in supercapacitor electrodes. [Chen et al. \(2021\)](#) studied the influence of the silica template effect on the activated carbon formation process from RHs by pre-treatment at various concentrations of NaOH or K_2CO_3 solution, followed by activation of KOH. The authors found that the selective leaching of silica before the activation process affects the structural characteristics of the formed pores. Pre-treatment with both NaOH and K_2CO_3 leads to an increase in the SSA of the resulting activated carbon. The best results were obtained with K_2CO_3 pre-treatment when the SSA increased by 94.29% compared to untreated coal and reached $2556.8\text{ m}^2/\text{g}$. The electrode created based on the obtained activated carbon with an electrolyte of 6 M KOH reaches a specific capacity of up to 325 F/g at a current density of 0.5 A/g and functions stably after 10,000 cycles.

In [Xue et al. \(2020\)](#) hierarchical porous carbon was obtained from RHs by carbonization and activation with the removal of the silica template. The initial RH was preliminarily treated with urea to introduce nitrogen-containing groups into the structure of the nanoporous material. The resulting best sample, 4NPC-800, has SSA of $416\text{ m}^2/\text{g}$, has hierarchical porosity, and contains a low pore volume of $0.29\text{ cm}^3/\text{g}$, which is composed of micro-, meso- and macropores. Despite the small SSA, a distinctive feature of the obtained nanoporous material is a high nitrogen content of up to 6.01 at%. The authors found that due to the structural features and high nitrogen content, the 4NPC-800 sample showed a high gravimetric capacity of 242 F/g and a high volumetric capacity of $306\text{ F}/\text{cm}^3$ at 0.5 A/g with 1 M H_2SO_4 electrolyte and possessed exceptional cycle stability. Using the 4NPC-800, a symmetrical supercapacitor was assembled that achieves a gravimetric energy density of $12.04\text{ Wh}/\text{kg}$ at $469\text{ W}/\text{kg}$ and a volumetric energy density of $15.24\text{ Wh}/\text{L}$ at $594\text{ W}/\text{L}$.

In [Yeleuov et al. \(2020\)](#) using a two-stage chemical procedure, activated carbon was synthesized with SSA of $3292\text{ m}^2/\text{g}$, which contains a few layers of graphene. Electrodes based on the obtained material have a specific capacity of 236 F/g at a current density of 0.5 A/g. The surface of the resulting nanoporous material was additionally modified with various amounts of $Ni(OH)_2$. The authors found that the specific capacity of the modified nanoporous material at a content of 9 wt.% $Ni(OH)_2$ reaches 300 F/g at a current density of 0.5A/g, which is an increase in capacity by 27% relative to the unmodified material. In addition, electrodes based on modified 9 wt.% $Ni(OH)_2$ retains the structural integrity and stability of electrode performance when tested up to 2000 charge-discharge cycles.

Intensive research is underway to obtain hierarchical nanoporous materials with a large SSA from a wide variety of biomass waste ([Lin et al., 2022](#); [Wan et al., 2020](#); [Ning et al., 2022](#)). In [Lin et al. \(2022\)](#) to obtain a highly porous carbon material, a new approach was used, which consisted of the preliminary polymerization of β -cyclodextrin (CD) with epichlorohydrin. The obtained cyclodextrin polymer was subjected to carbonization at a temperature of $500\text{ }^\circ\text{C}$ and subsequent activation at a temperature of $800\text{ }^\circ\text{C}$ in a nitrogen atmosphere. The three-dimensional network structure of the polymer made it possible to obtain a hierarchical nanoporous carbon material with an ultra-high surface area of $3710\text{ m}^2/\text{g}$ with a pore volume of $2.03\text{ cm}^3/\text{g}$. Supercapacitors made based on the obtained material have a capacity of 416 F/g and retain it at 100% after 10,000 cycles at a current density of 0.5 A/g with an electrolyte of 6 M KOH.

In [Wan et al. \(2020\)](#) studies on obtaining a nanoporous carbon material from orange peels using an unconventional activating agent, copper carbonate was carried out. The authors note that the orange peel was chosen because it contains large amounts of carbon, oxygen, nitrogen, and sulfur. The nanoporous material was obtained by one-stage heat treatment at temperatures of $700\text{--}900\text{ }^\circ\text{C}$ by pyrolysis in an argon atmosphere. The best samples with a hierarchical structure and doped

with a significant quantity of nitrogen, oxygen, and sulfur heteroatoms with SSA of $912.4\text{ m}^2/\text{g}$ were obtained at an activation temperature of $800\text{ }^\circ\text{C}$. The authors explain the preference for a temperature of $800\text{ }^\circ\text{C}$ by the optimal regime of the etching effect of copper carbonate. The resulting nanoporous carbon has a specific capacity of 375.7 F/g at 1 A/g. The symmetrical supercapacitor assembled based on the obtained material provides a high energy density of $31.3\text{ Wh}/\text{kg}$ at a specific power of $499.5\text{ W}/\text{kg}$ and retains 92.7% capacity after 50,000 charge/discharge cycles.

The authors of [Lin et al. \(2022\)](#), [Wan et al. \(2020\)](#), [Ning et al. \(2022\)](#) used succulent leaves as the raw material for obtaining nanoporous carbon. The nanoporous material was obtained by one-stage carbonization at a temperature of $800\text{ }^\circ\text{C}$ in a nitrogen atmosphere. Thermochemical activation was carried out using a double activating agent, which is a mixture of magnesium nitrate ($Mg(NO_3)_2 \cdot 6H_2O$) and zinc chloride ($ZnCl_2$). To dope the nanoporous material with heteroatoms of sulfur and nitrogen, thiourea was added to the initial mixture. The obtained N-S-HPC material has a three-dimensional hierarchical porous structure with SSA $2136.2\text{ m}^2/\text{g}$ and is doped with oxygen atoms (6.8%), nitrogen (9.5%) and sulfur (2.21%). Electrodes based on N-S-HPC achieve specific capacitance up to 455.3 F/g at 1 A/g. Symmetric supercapacitors assembled based on N-S-HPC, when using 1 M H_2SO_4 electrolyte, have a maximum specific energy of $10.3\text{ Wh}/\text{kg}$ at $250\text{ W}/\text{kg}$, and when using 1 M Na_2SO_4 electrolyte, the maximum specific energy almost doubles and reaches $19.89\text{ Wh}/\text{kg}$ at $450\text{ W}/\text{kg}$.

As can be shown in the previous item carbon aerogels with a high SSA, and heteroatom doping are promising electrodes for supercapacitors. [E et al. \(2021\)](#) synthesized porous N-doped carbon aerogels with an interconnected honeycomb structure using cellulose as the precursor and polypyrrole as the nitrogen source by using ice crystals as a template, along with a facile CO_2 activation treatment. Application prepared carbon aerogels as the electrode materials for supercapacitors exhibits a high specific capacitance ($160\text{ F}/\text{g}$), good charging/discharging rates, and excellent cycling stability. [Zhou et al. \(2021\)](#) synthesized the N—O—P co-doped porous carbon aerogel through a simple and green one-step process selecting the low-cost and abundant radish as the precursor. The N—O—P co-doped carbon aerogel exhibits a high gravimetric specific capacitance of $352\text{ F}/\text{g}$ at a current density of 1 A/g in the three-electrode system using 6 M KOH as the electrolyte. Besides, the material also exhibits a high specific capacitance retention rate of 78.4% by increasing the current density from 1 to 10 A/g. In 10,000 cycles of charging and discharging performance, the N—O—P co-doped aerogel exhibits excellent cycle stability with only a slight capacitance loss of less than 10%. [Zhao et al. \(2022\)](#) prepared a highly graphitized N self-doped hierarchical porous carbon aerogel conductive frame using chitosan as a biomass carbon source. The result shows that prepared carbon aerogel-based composite exhibits a large specific capacitance and excellent capacitance retention rate in a three-electrode system.

Thus, the analysis of the ongoing research shows that a large specific surface contributes to an increase in the specific capacitance of supercapacitor electrodes. The main reason for this is the increase in micropores concentration. However, the only microporous structure of activated carbons prevents the migration of electrolyte ions in the electrode structure during the formation of a double electric layer and thereby limits the availability of the electrode surface for charge accumulation. Therefore, when synthesizing activated carbons for supercapacitor electrodes, it is necessary to create a hierarchical porous structure, which should contain a given ratio of macro-, meso-, and micropores. An analysis of the literature also shows that one of the promising directions for increasing the capacitance of supercapacitors is the doping of carbon material with heteroatoms, which form bridges for charge transfer and increase the capacitance of supercapacitors. In particular, the review of the literature shows that the doping of activated carbon with N and S atoms increases the specific capacitance of the electrode material by increasing the surface wettability, changing the type of conductivity, and electrical conductivity, and creating active

nitrogen surface centres that promote the formation of redox centres that induce additional pseudo-capacitance. In connection with the foregoing, at present, the problems associated with the development of new strategies for the synthesis of activated carbon with desired properties that will ensure the accumulation of charges and their free transport in energy storage systems remain an urgent task.

3.2. Anode materials for alkali metal ion-batteries

LIBs are currently one of the most common devices for energy storage. These devices consist of an electrolyte and two electrodes, a cathode, and an anode, which are connected to an external circuit. The cathode is a lithium salt electrolyte placed on aluminum foil, and the anode is a carbon material deposited on a metal current collector. An electric current is created when charged particles move lithium ions to the cathode and electrons to the anode. When all the particles reach the electrode they need, the battery is discharged. When charging, the reverse process occurs. The main constituent materials of LIBs are electrolyte, separator, cathode, and anode. The cathode material occupies a large share (the mass ratio of cathode and anode materials is from 3:1 to 4:1). The most used anode materials are LTO (lithium titanate), surface functionalized silicon, powder graphite and high-performance graphene, conductive additives, activated carbon and carbon black. As cathode materials in LIBs, lithium cobalt (LiCoO_2) (J. D. Wang et al., 2022), spinel nickel-manganese (LiMn_2O_4) (Sharifidabad et al., 2022; Nwachukwu et al., 2022), lithium ferro-phosphate (LiFePO_4) (Nwachukwu et al., 2022) are currently used, which are practical due to their increased energy density, high-capacity, and speed. The type of cathode material has a significant impact on the energy density, power density, safety, service life and cost of the battery, and the problem of developing new anode and cathode materials for LIBs does not lose its relevance. Developments to improve the electrochemical characteristics of these materials are aimed at solving problems related to ensuring safety and reducing their cost. To solve these problems, the main research is aimed at the development of various materials with target properties and morphology. Xia et al. (2021) successfully synthesized the chestnut shell fluff-NiS/C anode material, which is used as a superior performance anode for LIBs, shows fine cycling stability and rate performance and maintains a good specific capacity of 411.6 mAh/g after 100th cycle (Fig. 4a). Liang et al. (2022)

designed a composite material that porous ZnO crystals embedded on the surface of hollow carbon spheres derived from RH (Fig. 4b). The material had a high discharge specific capacity, e.g., 1111 mAh/g after 150 cycles. Zhao et al. (2022) fabricated the porous 3D-carbon framework@ TiO_2 hybrids by using rape pollen as raw materials (Fig. 4c). The microstructure and morphology of obtained materials had been studied by scanning electron microscope (SEM) analysis and established that they had hierarchical porous hollow structure. That structure led to an increase in the SSA, which delivers high reversible specific capacity. He et al. (2022) prepared a porous carbon framework using the grape stem as the biomass carbon source by facile approach. Moreover, the composite accommodated the Si NPs inside the matrix to further improve the capacity. The composites showed excellent lithium storage capability and high reversible charge capacities of 891 mAh/g after 400 cycles at 0.2 A/g.

There is also an intensive search for new electrochemical systems that could compete with LIBs. As an alternative to LIBs, KIBs hold great promise due to the prevalence of potassium. The main problems in the creation of KIBs remain their high flammability, limited charge, and discharge cycles, since not only potassium reacts with oxygen, but also carbon on the anode. Deng et al. (2021) developed bagasse-derived Ni-doped 3D porous carbon materials as an anode material for use in KIBs (Fig. 4d). The obtained materials demonstrate that the formation of the porous structure activation with NiCl_2 and nitrogen doping is a key role. Moreover, the application of carbon materials as an anode material for KIBs are shown superior performance such as a reversible capacity of 100.4 mAh/g at a current density of 200 mA/g over 400 cycles. Wang et al. (2022) prepared the N self-doped carbon quantum dots (N—CQDs) using soybean as the raw materials by the hydrothermal method. The obtained material was used as the anode materials in KIBs and the results with honeycomb carbon delivered a high specific capacity of 280.5 mAh/g at 0.1 A/g.

In Table 4, last year obtained biomass-derived anode materials used in lithium- and KIBs and their electrochemical performance are collected. The comparison of the electrochemical performance of the anode materials used for lithium- and KIBs are shown despite bagasse and soybean-based anode materials used for KIBs having a high surface area, the capacity of batteries is low. RH and rape pollen-based anode materials used for LIBs have a low surface area, and the capacity of batteries is high. This dependence can be associated with the pore size,

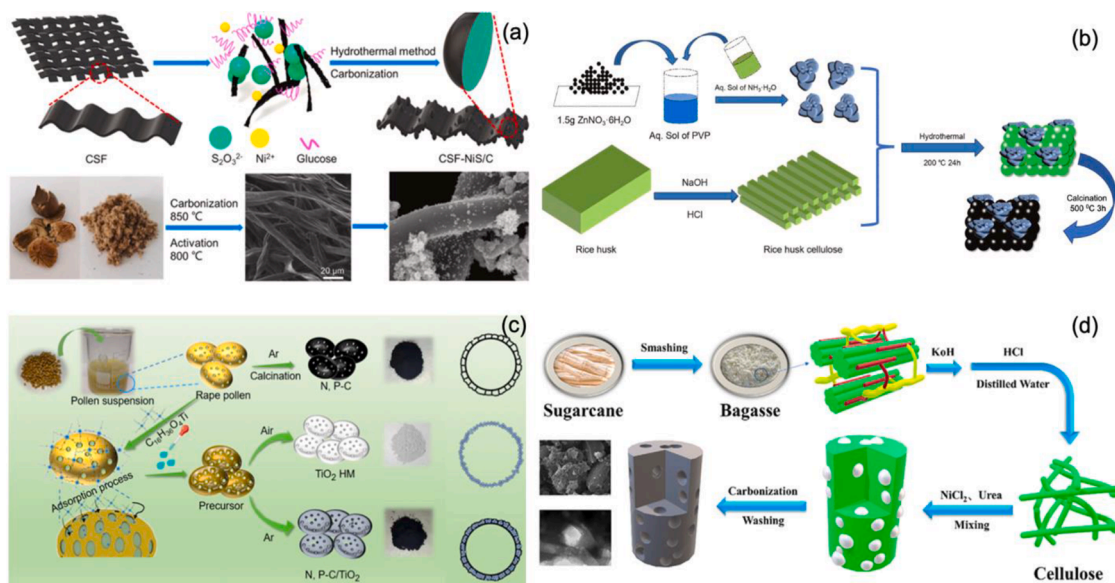


Fig. 4. Schematic illustration of the synthetic process of biomass-derived porous carbon materials: (a) hydrothermal method along with an annealing treatment (Xia et al., 2021); (b) hydrothermal method (Liang et al., 2022); (c) sol-gel method (J. J. Zhao et al., 2022); (d) carbonization and further activation (Deng et al., 2021). Reprinted with permission from (Liang et al., 2022; J. J. Zhao et al., 2022; Deng et al., 2021; Xia et al., 2021).

Table 4

Electrochemical performance of biomass-derived anode materials in batteries.

Type of battery	Biomass	Microstructure	SSA, m ² /g	Current density, A/g	Cycle number	Capacity, mAh/g	Ref.
LIBs	RH	Porous carbon	94.375	0.2	150	1111	(Liang et al., 2022)
LIBs	Rape pollen	Hierarchical	69.6	0.1	200	687.3	(J. J. Zhao et al., 2022)
LIBs	Grape stem	–	–	0.2	400	891	(He et al., 2022)
LIBs	Chestnut shell fluff	3D interconnected microbelt structure	–	–	100	411.6	(Xia et al., 2021)
KIBs	Bagasse	Three-dimensional porous carbon	466.621	0.2	400	100.4	(Deng et al., 2021)
KIBs	Soybean	Honeycomb porous structures	242.6	0.1	100	280.5	(D. D. Wang et al., 2022)

which plays an important role in the processes of ion intercalation into the anode material.

4. Conclusion

Due to the high rates of development of agriculture, many of its branches accumulate a huge amount of biomass-derived raw materials, and the technologies for their processing are ineffective and damage the environment. On the other hand, biomass is an ideal natural material to produce porous carbon, which finds application in a wide variety of fields, including the energy industry. In modern society, a significant part of the energy is produced by burning organic fossil fuels, which depletes non-renewable energy resources, and pollutant emissions worsen the ecological situation. Renewable energy sources such as wind, solar, hydro, and geothermal energy contribute to environmental and energy security. However, the main disadvantage of these branches of the electric power industry is the lack of effective technologies that allow the accumulation and storage of electricity on an industrial scale. Supercapacitors and batteries are a new type of environmentally friendly and most efficient energy storage that can solve the problem of storing electricity on an industrial scale. Modern advances in the field of application of various biomass-derived porous carbon materials, such as activated carbon and carbon aerogels as electrode and anode materials in supercapacitors and batteries, discussed in detail in this manuscript, demonstrate the achieved over the last 3–5 years of progress in the preparation of the electrode and anode materials with high-performance, as well as progress in solving environmental problems associated with the disposal of plant waste and expanding the use of renewable energy sources.

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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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