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Review

Treatment of Biowaste for Electrodes in Energy Storage Applications: A Brief Review

Samuel Ebenezer Kayode and Francisco J. González *

Facultad de Ciencias Químicas, Universidad Autonoma de Coahuila, Unidad Saltillo, Saltillo 25280, Coahuila, Mexico
* Correspondence: fgonzalezgonzalez@uadec.edu.mx

Abstract: Proper and innovative waste management methods still pose a major concern in our present world. Continuous accumulation of biowaste from bio-processing industries, household, organic residues and so on makes the environment polluted and endangers the health of man and other animals. The common waste management methods which include direct dumping into water bodies, open-air combustion, and as land fillers are obsolete and are the major causes of environmental pollution. Conversion of biowastes into valuable materials aids proper waste management, and helps to attain a cleaner environment, in addition to the fact that wastes are turned into wealth. Biowastes are rich in carbon and can serve as excellent precursors for the synthesis of important carbon materials such as activated carbon, graphene, carbon nanotubes etc. Three important methods of converting biowastes into carbon materials are discussed in this review. The electrochemical, adsorption, and electrocatalytic properties of the materials and the applications in electrochemical energy storage devices are also discussed in brief. This review focuses on the synthesis of carbon materials from biowaste residues and their use in developing electrode materials for batteries and supercapacitors. Future perspectives on the need to exploit greener technology for the conversion of biowastes into important carbon materials should be considered.

Keywords: environmental pollution; biowastes; carbonization; activated carbon; specific surface area; electrode performance

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1. Introduction

Biowaste residues are materials that are often generally referred to as waste by individuals, families, and bio-processing industries. The reason is that these materials seem not to be directly useful to them, and therefore are disposed through the easiest available methods which include, direct dumping into water bodies, burning in open air, or as land-filling materials as shown in Figure 1. During the burning and decay of biowaste materials, methane, carbon dioxide, and other toxic gases are generated and released into the environment. These methods of waste management are obsolete and hazardous to the plants, animals, humans, and other non-living components that constitute the environment. Meanwhile, continuous gathering of waste in the environment over a long period of time also pose ecological challenge. Processing of biowastes into useful materials aids proper disposal of wastes which in turn help to attain cleaner environment. Other methods such as vitrification, in which the ash obtained from carbonization of biowastes is subjected to very high temperatures of about 1500 °C to obtain glass-ceramic materials, has been reported as a facile and important method for waste disposal [1–3]. These biowastes such as rice husks, ground nut shells, sugarcane bagasse, spent coffee ground, brewers' spent grains, corncob, coconut shells, wheat husks, and palm kernel shells among others are generated globally in very large amount every year, they are therefore readily available and at no cost [4].

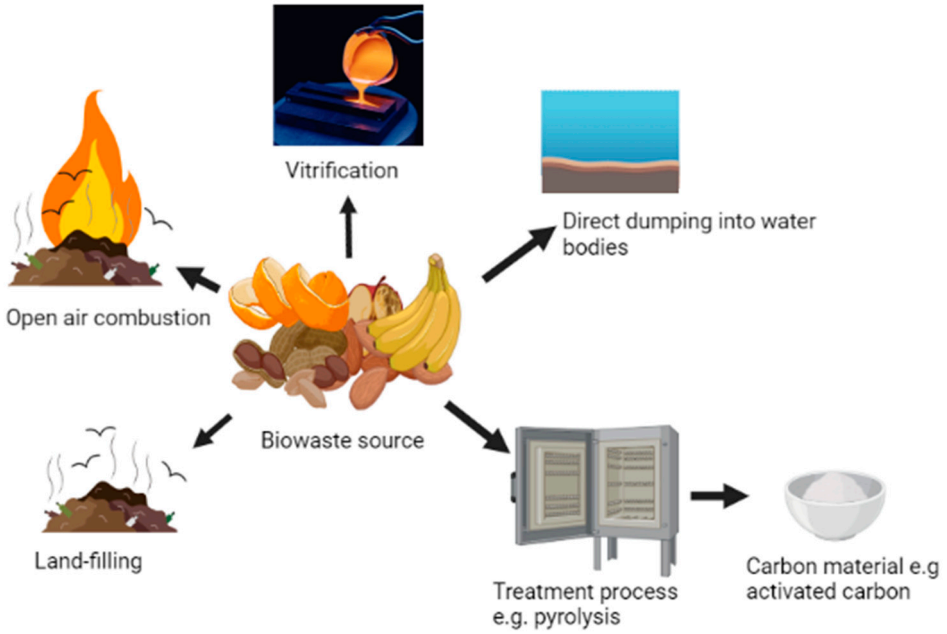


Figure 1. Different approach for managing biowaste materials.

For instance, about 700 million tons of rice is produced globally every year, of which nearly 20% by weight comprises husk which is not edible. This amounts to about 140 million tons of rice husk generated per annum [5]. The average amount of waste from groundnut shell is estimated to be between 350 and 400 g per kg of shells produced [6]. Annual global production of sugarcane is estimated to be about 1.6 billion tons, from which about 279 million metric tons of sugarcane bagasse is generated [7]. The industrial processing of coffee is another important source of biowaste to investigate. Spent coffee grounds are recovered as waste after the consumption of coffee. It is estimated that only about 30% of the annual coffee beans produced can be extracted into coffee for consumption, meaning that approximately 70% of the annual coffee beans produced globally are disposed as waste [8]. Similarly, the brewery industry also creates large amount of waste which is economically difficult to deal with [9].

The environmental impact, specifically water and earth pollution, along with the energy demand, is nowadays a serious challenge that face humanity [10,11]. In the case of water, the scarcity and contamination of water sources such as rivers or lakes, are topics of concerning interest, where low-cost technologies such as membranes and adsorbents for metals and other pollutants are stated to be some of the most promising ones [12,13]. On the other hand, developed countries around the world have been recently making efforts to achieve zero-carbon-emissions. This includes minimizing human activities such as combustion of fossil fuels which causes emission of greenhouse gases, promoting the removal of residual greenhouse gases to achieve zero emissions. In 2020, over 100 countries have devoted themselves to taking actions toward achieving zero-carbon-emissions, it is expected that other countries around the world will follow this movement to achieve the global goal [14]. One of the major steps that has been taken toward achieving this goal is to engage researchers by making funds available for research on the conversion of biowastes into important materials for different value-added applications. Variety of treatment processes, such as hydrothermal, pyrolysis, activation, chemical exfoliation, electrochemical, and freeze drying along with others, have being explored to convert biowastes into important materials. These materials find potential applications in energy storage devices, environmental remediation, biosensors, drug delivery, tissue engineering, and so on, either directly or as composites where they are blended with other materials such as metals or polymers.

Different naturally abundant biowastes have been reported for the synthesis of porous carbons due to their availability, high performance, and simple processing methods. Carbon exists in different structural forms, for example activated carbon, carbon nanotubes, aerogels, and graphene which contains large adsorption sites that are important for charge storage and transport. Because of these facts, carbon is an efficient electrode material for batteries and supercapacitors. The various structural forms of carbon that are commercially available for electrode preparation are expensive and not environmentally friendly because they are synthesized from non-renewable sources such as petroleum, coal, and natural gas [15,16]. Therefore, based on the efforts of the developed countries to achieve zero-carbon-emissions in the nearest future, coupled with the race to obtain cheap, abundant, and environmentally friendly carbon in various forms, research attention has in recent years focused on exploring various biowastes as cheap, abundant, and environmentally friendly source of carbon for electrochemical value-added applications.

This review highlights the processing of biowaste materials and their applications in energy storage systems. The review is centered specially in the treatments and preparation of electrode materials from biowaste sources for these applications.

2. Biowastes as Rich Source of Carbon Materials

Biowastes are in most cases composed of cellulose, hemicellulose, and lignin which are very rich carbon compounds. Focus on the use of carbon materials from biowaste for sustainable energy development has gained popularity in materials research [15,17–22], it is without doubt because of the high carbon contents of the biowastes as evidently presented in Tables 1 and 2, which make them excellent precursors for the preparation of high-quality materials and nanomaterials. Techniques that have been employed for the conversion of biowastes into carbon materials for different applications include pyrolysis, activation, and hydrothermal treatment among others.

Table 1. Ultimate analysis reports of some biowastes.

Biowaste	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Oxygen (%)	Reference
Rice husk	35.82	6.15	5.57	51.95	[23]
Orange peel	45.10	8.78	0.46	42.30	[24]
Coconut shell	42.31	4.65	0.57	52.03	[25]
Sugarcane bagasse	44.60	5.80	0.60	44.50	[26]
Corncob	45.69	6.18	5.65	41.65	[27]
Brewer's spent grain	43.59	6.18	3.46	37.22	[28]
Jute stick	43.41	5.78	7.81	43.00	[29]
Groundnut shell	46.82	6.58	0.80	37.64	[30]
Spent coffee grounds	59.70	7.80	2.20	30.20	[31]
Banana peel	45.43	5.67	2.31	36.40	[32]
Apple pomace	41.70	7.80	0.60	48.10	[33]
Olive mill solid waste	44.10	6.30	1.60	35.80	[33]
Grape seed	47.40	6.70	1.90	38.50	[33]
Grape skin	48.60	7.00	3.00	33.20	[33]
Almond shell	49.62	5.98	0.17	44.23	[34]
Nutshell	48.79	5.99	0.38	44.84	[34]

Table 2. Ultimate analysis reports of some biochar.

Biochar Precursor	Carbonization Temperature (°C)	C (%)	H (%)	N (%)	O (%)	Reference
Corncob	1200	89.31	0.45	1.56	-	[33]
Olive mill solid waste	1200	70.76	0.39	2.27	-	[33]
Almond shell	873	85.50	5.28	1.70	7.52	[34]
Nutshell	873	81.13	6.11	1.20	11.56	[34]

2.1. Methods for Converting Biowastes into Value-Added Carbon Materials

2.1.1. Pyrolysis

Pyrolysis is a process that converts organic matter such as plants or animal residues into carbonaceous materials by subjecting them to high temperatures [35]. Dry biowaste material such as sugarcane bagasse, corncob, coffee shells, rice husk, etc., are exposed to high temperatures of about 700 °C in a furnace in an inert environment (usually nitrogen or argon atmosphere), to evaporate and remove the hydrocarbon contents in an oxygen-free environment. The product obtained from this process is called char or biochar [36]. Bai's group reported the preparation of hierarchical porous carbon from pulp and paper wastes (lignosulphonates) for high-performance supercapacitor electrode via pyrolysis. The pretreated biowaste was pyrolyzed at 900 °C for 2 h in Ar atmosphere followed by $ZnCl_2$ activation at 900 °C for 3 h [37].

2.1.2. Hydrothermal Method

This method is also referred to as high-pressure or high-temperature aqueous carbonization. During hydrothermal treatment, the biowaste is heated at a temperature of about 200 °C in an airtight reactor, usually an autoclave, in the presence of superheated water and self-generated pressure [38]. This process is used to prepare materials with controlled structures [39]. In an experiment, Liu's group synthesized porous carbon from waste coffee grounds for supercapacitor application following hydrothermal synthesis method. They combined catalytic carbonization using $FeCl_3$ as catalyst with KOH activation at 700 °C, followed by hydrothermal treatment of the resulting carbon material at 120 °C for 6 h to obtain an activated carbon with well-defined porosity (1.64 $cm^3\ g^{-1}$ pore volume) and ultrahigh specific surface area of 3549 $m^2\ g^{-1}$ suitable for applications in energy storage devices [40].

2.1.3. Activation

Activation of char produced from the pyrolysis process are classified into physical activation and chemical activation. In the physical one, the char is heated at temperature between 800 and 1100 °C in steam, CO_2, N_2, or air mixture environment [41]. While in chemical activation, the char produced from pyrolysis is combined and mixed with activating agents such as KOH, NaOH, $ZnCl_2$, H_3PO_4, K_2CO_3, and $FeCl_3$ in suitable ratios and then heated at a temperature of 800 °C or above to obtain activated carbons with desired properties [42]. Over the past few decades, activation of carbonaceous materials to obtain activated carbon has gained tremendous recognition because of the simplicity, time saving, and cost effectiveness. Activation can be either a one single step or a two-step process which is often preceded by low temperature carbonization or hydrothermal treatment, which helps to control the porosity and surface area of the activated carbon obtained. For instance, Jiang et al., 2020 obtained activated carbon from peanut shell via a two-step activation process. First, hydrothermal carbonization of pulverized peanut shell was carried out at 200 °C for 4 h followed by $ZnCl_2$ activation at 800 °C for 90 min [43].

3. Features of Carbon-Based Electrodes

Two important features that carbon electrode materials should possess are, to be a good electrocatalyst and adsorbent. These features define the applicability of the carbon electrode material in electrochemical energy storage systems.

3.1. Electrocatalysis

Electrocatalysis is a process which leads to increasing the speed (rate) of half-cell reactions at the surfaces of electrodes. An electrocatalyst is a catalyst that takes part in electrochemical reactions. They are substances which particularly cause the increase in the speed of half-cell reactions. Electrocatalysts function at electrode surfaces and most commonly may be that electrode surface itself. All-round importance of electrocatalysis in scientific research cannot be overemphasized. Fields such as wastewater treatment,

energy devices, corrosion science, electro-organic synthesis, and development of electro-analysis sensors actively engage the applications of electro-catalysis [44]. The properties of a good electrocatalyst include excellent catalytic activity, high surface area, stability toward anodic corrosion, low energy consumption, and outstanding mechanical and chemical resistance [45].

Electrocatalysts are required to increase the rate of slow electrochemical reactions such as oxygen evolution, oxygen reduction, and hydrogen evolution reactions, which are essential reactions in renewable energy technology. To find alternatives to the existing and expensive metal-based electrocatalysts (e.g., platinum), metal-free heteroatoms such as N, S and P, doped with carbon have been reported as efficient catalysts. A potential electrocatalyst for zinc-air battery was prepared by co-doping porous carbon from garlic stems with nitrogen and sulfur [46]. The electrocatalyst synthesized showed improved oxygen reduction reaction activities with high power density and better stability compared with the platinum/carbon electrocatalyst. Zhang et al. also prepared an electrocatalyst by co-doping nitrogen and phosphorous with graphene oxide. The bifunctional catalyst (i.e., the material prepared acted as both electrode and catalyst) facilitates fast oxygen reduction and hydrogen evolution reactions toward a zinc-air cell [47]. The material is a potential bifunctional catalyst for green energy technology.

3.2. Adsorption

Adsorption process involves the movement and gathering of dissolved particles on the surface of an adsorbent material. This process can occur because of physical forces (physisorption) or chemical bonds (chemisorption). It is a reversible process; the reversed process is called desorption [48]. A good adsorbent possesses the following characteristics: excellent capacity, high sorption rate, good selectivity, fast kinetics, and low-cost. The texture, surface morphology, chemical composition of material and chemical activation (functionalization) are important factors which determine the sorption capacity of an adsorbent [48,49]. Physisorption occurs due to weak Van der Waals' attraction forces and because the adsorbent generally has low specific surface area and is non-porous in nature. Meanwhile, chemical adsorption (chemisorption) occurs because of moderately strong chemical connections at the adsorbates-adsorbent interfacial functional groups [48]. The adsorption process is anchored on the physicochemical parameters of the adsorbent material. They include solubility, size of molecule, surface charge, chemical composition, reactivity, and hydrophobicity. Generally, the existence of many functional groups aids the adsorption and storage of electric charges on the surface of the carbon electrode [48,50].

4. Biowaste-Based Activated-Carbon and Their Applications in Energy Storage Systems

4.1. Batteries

Electrochemical cells can either produce electrical energy from chemical reactions or utilize electrical energy to generate chemical reactions. Batteries are electrochemical cells that utilize reversible redox reactions to produce and store electrical energy. The energy stored in a battery can be used to power electrical devices such as portable electronics (e.g., cell phones) and electric vehicles. Conventional batteries include lithium-ion batteries (LiIBs), lithium-sulfur batteries (LiSBs), sodium-ion batteries (NaIBs), and metal-air (metal-oxygen) batteries [51]. The four basic parts of batteries include cathode, anode, electrolyte, and separator (membrane). Biowastes has been reported to be good precursors for the preparation of electrode materials for battery applications. Table 3 shows the electrochemical performance of some recently reported biowaste-derived activated carbons.

Table 3. Electrochemical performance of some reported biowaste-based activated carbon for battery applications.

Biowaste Source	Treatment	Specific Capacity (mAh/g)	Coulombic Efficiency (%)	Cycle Number	Application	Reference
Spent coffee grounds	KOH activation	592 at 100 mA/g	97	500	LiIB	[52]
Coconut shell	KOH activation	150 at 0.1 A/g	–	1500	AlIB	[53]
Rice husk/waste coffee grounds	Carbonization	1125 at 100 mA/g	–	100	LiIB	[54]
Corncob	Carbonization	268.54 at 24.80 mA/g	73.49	–	NaIB	[33]
Grape skin	Carbonization	243.82 at 24.80 mA/g	61.89	–	NaIB	[33]
Grape seed	Carbonization	244.94 at 24.80 mA/g	60.25	–	NaIB	[33]
Apple pomace	Carbonization	247.19 at 24.80 mA/g	40.73	–	NaIB	[33]
Olive mill	Carbonization	174.16 at 28.80 mA/g	50.00	–	NaIB	[33]
Palm kernel shell	KOH activation	869.8 at 200 mA/g	–	100	LiSB	[55]
Rice husk	Carbonization	632 at 1.0 A/g	70.4	100	NaIB	[56]

i. *Cathode*: Cathode is the positive electrode that acquires electrons from the external circuit. Reduction reactions normally take place at the cathode. Electrons move from the anode into the cathode while conventional current flow out from the cathode. The chemical reactions that occur around the cathode make use of the electrons from the anode.
ii. *Anode*: Anode is the negative electrode from where electrons flow to the cathode through the external circuit. Conventional current flows into the anode from the cathode. The chemical reactions that occur at the anode-electrolyte interphase causes a build-up of electrons in the anode of a battery. These electrons are prevented by the membrane from moving to the cathode through the electrolyte but move from the anode through the external circuit into the cathode.
iii. *Electrolyte*: The electrolyte provides the medium for ion transport mechanism between the two electrodes of a cell. Electrolytes could be in aqueous or molten form containing dissolved salts, acids, or alkalis that are necessary for ionic conduction. Nevertheless, some conventional batteries contain solid electrolytes that work as ionic conductors at ambient temperature.
iv. *Separators*: The separator is a porous material which separates and avoid the anode and cathode from touching each other, which could result in short circuit in the battery. Different materials such as cotton, nylon, polyester, cardboard, and synthetic polymer films are used to prepare the separator. Separators are chemically unreactive toward electrolyte and the electrodes.

4.2. Lithium-Ion Batteries (LiIBs)

LiIBs are rechargeable battery composed of cells containing lithium ions. When a LiIB is in use (i.e., during discharge), lithium ions (Li^+) move from the anode to the cathode, while during charging, the reverse reaction occurs. Carbon materials are normally used as anode in the conventional lithium-ion cells, the cathode is made of typical metal oxide while the electrolyte composed of lithium salt is dissolved in organic solvent [57]. In a typical LiIB, the following reactions occur during charging and discharging processes [58].

At the positive electrode (cathode) (where lithium is doped with cobalt oxide)

$$CoO_2 + Li^+ + e^- \rightleftharpoons LiCoO_2$$

At the negative electrode (anode) (graphite)

$$LiC_6 \rightleftharpoons C_6 + Li^+ + e^-$$

The overall cell reaction is

$$LiC_6 + CoO_2 \underset{\text{charging}}{\overset{\text{discharging}}{\rightleftharpoons}} C_6 + LiCoO_2$$

To improve the performance of LiIB, an important aspect to concentrate attention is how to obtain suitable electrode materials, which determine the energy density of batteries. Carbon materials in different forms such as mesoporous carbons, carbon nanotubes, carbon nanofibers, graphene, carbon spheres etc., have been extensively studied and were reported to possess high theoretical specific capacity compared to graphite. This can be seen because of increased storage capacity for lithium ions in the high surface area materials [59].

Interestingly, the synthesis of carbon materials from biowaste residues offer a more convenient and economical alternative. The raw materials are abundant and do not need difficult techniques for treating and processing materials. For instance, in a report by Kwon et al. [60], a composite which was prepared from silicon and carbon material from corn starch was used to fabricate an electrode which was used as anode in a LiIB. The anode presented a capacity of 1800 mAh g^{-1} and a capacity retention of 80% after 500 cycles. Moreover, the composite anode was tested in a Li-ion cell using commercial cathodes showing long-term cycling stability at 1 C during 500 cycles. An excellent electrochemical performance of the electrode was recorded which suggests the applicability of corn starch carbon material in LiIBs. In another report [59], graphitic porous carbon sheet with specific surface area of 1246 m^2 g^{-1}, synthesized via KOH activation and carbonization of jute stick which was used as anode material in LiIB. This material was reported to demonstrate high specific capacity and outstanding specific capacity retention. These and many other biowaste materials that have been previously studied prove to be promising electrode materials for LiIBs applications.

4.3. Sodium-Ion Batteries (NaIBs)

NaIBs are rechargeable batteries analogous to the LiIBs, but charges are carried by sodium ions (Na^+) instead of the Li^+. The working principle and the cell construction of NaIBs are like those of the LiIB types that have gained commercial recognition. A major advantage of NaIBs over LiIBs is the abundance of sodium in nature. Therefore, commercial production of NaIBs is expected to be cheap compared to LiIBs [61].

NaIB cells are made up of cathodes which are based on materials that contain sodium, and the anode is made of inert materials and electrolyte which can be an aqueous or non-aqueous solution of sodium salt. The aqueous electrolytes have the disadvantage of producing low voltage due to the limited electrochemical stability window of water. Therefore, non-aqueous electrolytes such as sodium hexafluorophosphate are often preferred because of their ability to extend the window range [62–64]. During the charging process, sodium ions are removed from the cathode and migrate into the anode where at the same time, electrons travel through the external circuit from the cathode into the anode. The reverse process occurs during discharging. Due to the difference in the physical and electrochemical properties of sodium and lithium, materials generally used for LiIBs are not always suitable for NaIBs [65]. For instance, the graphite anodes used in LiIBs are not suitable for use in NaIBs because it cannot store the sodium ions in significant amount due to the large size of the ions. Rather, non-graphitizable, non-crystalline, amorphous carbon known as hard carbon is presently preferred as ideal sodium-ion anode. Hard carbon has an outstanding cycling stability, high capacity, and lower working potentials. Peanut shells [66], rice husk [61], walnut shells [67], apricot shells [68], apple [69] among others have been reported for the preparation of hard carbon to be use as anode materials in NaIBs applications.

4.4. Other Batteries

In metal-air electrochemical cells, the anode is usually a pure metal with an external cathode of ambient air and an aqueous electrolyte. When the battery is in use, reduction

reaction normally takes place at the air cathode and the anode undergo oxidation [70]. Metal-air batteries possess higher energy density and specific capacity compared to LiIBs. Because of this, MABs are becoming important potential candidate for applications in electric vehicles. The commercial application of MABs is faced with complications that are associated with challenges such as slow oxygen-reduction reactions at the cathode which has slow-down its development and commercialization [71].

Introducing electron-rich atoms into the carbon matrix to serve as catalyst for the acceleration of oxygen reduction reactions in air cathodes is found to be an encouraging solution to the problem of slow kinetics of the oxygen reduction reactions in MABs. Ma's group co-doped nitrogen and sulfur in porous carbon derived from the carbonization of garlic stems. The material obtained was used as cathode electrocatalyst with promising faster oxygen reduction reaction capability in a zinc-air cell [46]. In a similar report, heteroatoms such as nitrogen, sulfur, or phosphorus doped with graphene have also shown tremendous catalytic effectiveness toward oxygen reduction reactions [70,72]. Considering cheap, abundant, fast processing and sustainability, heteroatoms doped with carbon from biowaste sources can be utilized as an alternative of graphene-based oxygen reduction reaction electrocatalysts.

Another promising technology is the aqueous Zn-ion battery (ZnIB). In this type of battery, the working principle is the charge transfer between the Zn metal anode and the cathode [73]. They present lower cost and higher safety compared to Li-ion batteries because aqueous electrolytes are much safer than organic electrolytes commonly used for lithium salts. However, their narrow electrochemical window limits their applications and hinders their competence with Li-ion and other technologies. One method to improve their performance is with the addition of a conductive additive to the cathode, as it was reported by Li et al. [74], where they developed a cathode composed of sulfur and carbon nanotubes in a 50 wt.%. They obtained a capacity of 1105 mAh g^{-1} and an energy density of 502 Wh kg^{-1}, demonstrating the technical and economic feasibility of this type of cathode.

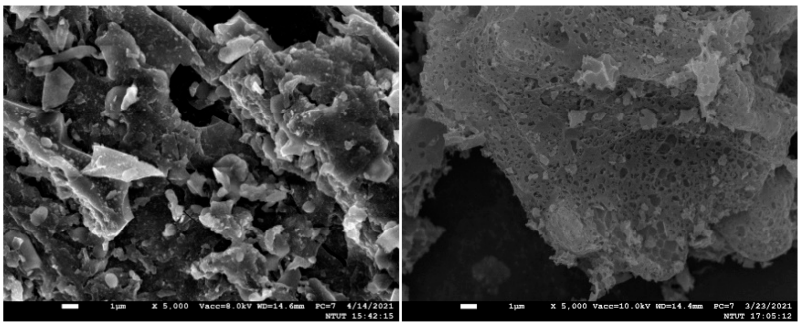
4.5. Supercapacitors

Supercapacitor is another type of energy storage device that stores and gives-out energy at a very fast rate, given the high current within a short time duration [75]. Activated carbon is possibly the most used material in supercapacitors due to its low cost, simple processing method, and high surface area [76,77]. The components and design of the supercapacitors are like those of the batteries. Supercapacitors are made up of electrode, electrolyte, current collector, binder, and separator/selective ion membrane. Although all the components have contributions to the storage performance of a supercapacitor, the electrode and electrolyte both play a major role. In supercapacitors, energy is stored as charges at the electrode–electrolyte interface, the extent of charge storage by the electrode is known as the capacitance. An important parameter to achieve high capacitance is the surface area. Electrodes that possess large surface area have capacity to store more charges and thereby have higher capacitance compared to those with small surface area. Based on the electrode materials, the supercapacitors can be classified into three categories which are: electric double-layer capacitors (EDLC), in which the working principle is based on the Helmholtz layer; pseudocapacitors based on faradaic reactions; and hybrid capacitors which combine both behaviors [78]. The carbon materials such as activated carbon, carbon aerogels, carbon nanotubes (CNTs), graphene etc., show the EDLC behavior. Nevertheless, other alternative materials and structures such as metal organic frameworks derivatives (MOF-D) have demonstrated promising characteristics toward this application [79]. These electrode materials are electrochemically passive, the charge storage takes place only due to the physical buildup of charges/ions on the electrode surface [80]. Table 4 shows the summary of the performances of some reported biowaste-based activated carbon in supercapacitor application.

Table 4. Performance of some reported biowaste-based activated carbon for supercapacitor applications.

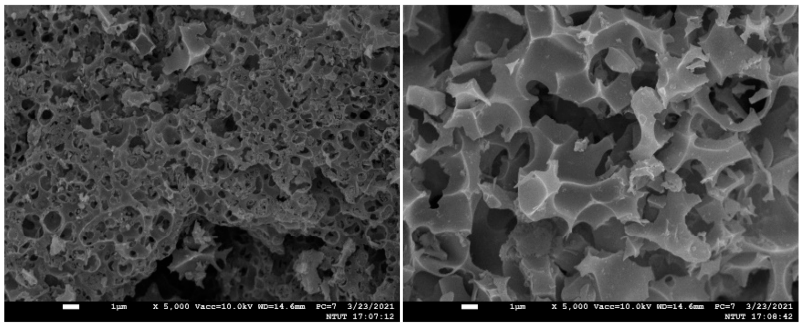
Biowaste	Treatment Method	Specific Surface Area (m^2/g)	Energy Density (Wh/Kg)	Power Density (W/Kg)	Specific Capacitance (F/g)	Current Density (A/g)	Reference
Peanut shell	$ZnCl_2$ activation	2129.5	32.08	1000.0	266.06	0.5	[43]
Waste coffee grounds	KOH activation	3549.0	101	900	224.0	1.0	[40]
Spent coffee grounds	hydrothermal/ carbonization KOH activation	1835	10.84	4589	312	0.1 & 3	[52]
Orange peel	$CuCO_3$ activation	912.4	31.3	499.5	375.7	1.0	[81]
Prosopis juliflora wood	KOH activation	2943.0	56.7	248.8	588.0	0.5	[82]
Corncob	KOH activation	1722.0	18.84	149.36	382.6	0.5	[83]
Lemon peel	KOH activation	744.78	4.67	8113.0	152.14	-	[84]
Rice hull	NaOH activation	768.0	31.9	309.2	150.8	0.5	[85]
Jute stick	$NaHCO_3$ activation	1100.0	20.0	500.0	150.0	1.0	[86]
Spent coffee grounds	CO_2 activation	2497.0	48.3	627.0	222.4	0.5	[87]
Banana stem	$ZnCl_2$ activation	788.09	6.19	44.67	179.0	-	[88]
Coconut shell	KOH activation	1567.0	48.9	1000.0	449.0	1.0	[89]
Sugarcane bagasse	Activation	1351.7	14.5	125.0	418.5	0.5	[90]

Activation process of biowastes allows to obtain porous materials with a wide range of pore size as it is shown in Figure 2. Lee et al. [89] prepared coconut shell activated carbon using different concentrations of KOH where they reported a superior surface area of KOH-treated samples (1178–1567 m^2 g^{-1}) in comparison with the not treated with KOH samples (282 m^2 g^{-1}). Liu's group synthesized porous carbon from waste coffee grounds for supercapacitor application following hydrothermal synthesis method. They combined catalytic carbonization using $FeCl_3$ as catalyst with KOH activation at 700 °C followed by hydrothermal treatment of the resulting carbon material at 120 °C for 6 h to obtain an activated carbon with well-defined porosity (1.64 cm^3 g^{-1} pore volume) and ultrahigh specific surface area of 3549 m^2 g^{-1} suitable for applications in energy storage devices. The material obtained demonstrated excellent potential toward supercapacitor application with energy density of 101 W h Kg^{-1} at 900 W Kg^{-1} power density with high capacitance of 440 F g^{-1} at 0.5 A g^{-1} in 6 M KOH aqueous electrolyte [40]. The porous carbon obtained by Bai's group showed excellent energy storage performance when used to assemble symmetry supercapacitor. It exhibits high-specific capacitance of 289 F g^{-1} at a current density of 0.5 A g^{-1} with high energy density of 40 W h Kg^{-1} at a power density of 900 W Kg^{-1} [37]. In another report, activated carbon obtained from peanut shell via chemical activation was found to possess large surface area of 2129.5 m^2 g^{-1} with good porosity. Electrochemical analysis revealed that the activated carbon obtained exhibited high specific capacitance of 266.06 F g^{-1} at 0.5 A g^{-1} current density with energy density of 32.08 W h Kg^{-1} at 1000 W Kg^{-1} power density [43].



(**a**) (**b**)

Figure 2. *Cont.*



(**c**) (**d**)

Figure 2. SEM micrographs of coconut-shell derived carbons without KOH (**a**) and at different KOH concentrations (**b**–**d**). Reproduced from MDPI [89].

5. Biowaste-Based Composites

Composite materials are prepared to: (i) improve on the performance (such as conductivity and cycle stability) of different metal oxides and conducting polymers such as polyaniline or polythiophenes (Figure 3), (ii) reduce cost, and (iii) reduce environmental hazards. Activated carbon, graphene, carbon nanotubes, and carbon aerogels are the often-used carbon nanomaterials for the preparation of nanocomposites. Carbon nanocomposites offer a high conductivity and specific surface area which is essential for charge adsorption and storage [91]. These carbon nanomaterials can easily be obtained from cheap, abundant, and eco-friendly biowaste sources as discussed in the previous sections. Example of some recently reported biowaste-based composites and their charge storage capacities are presented in Table 5 below.

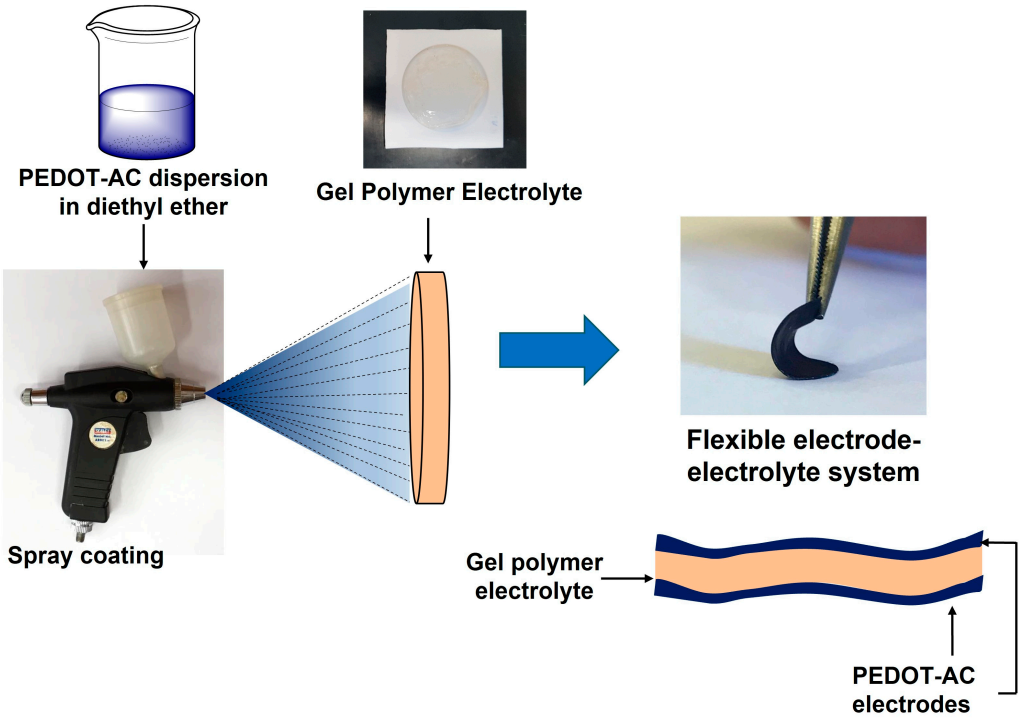


Figure 3. Scheme of preparation of poly(3,4-ethylenedioxythiophene) (PEDOT) and activated carbon derived from brewer's spent grain. Reproduced from MDPI [15].

Table 5. Performance of biowaste-based nanocomposites.

Biowaste Source	Composite Formed	Electrochemical Performance	Application	Reference
Fennel flower	poly-orthoaminophenol/functionalized graphene oxide/activated fennel flower	1400.2 F/g at 2 A/g	Supercapacitor	[92]
Rice husk	graphene/graphite	16007.02 F/g	Supercapacitor	[93]
Sugarcane bagasse	carbon spheres/graphene	226.8 F/g at 0.5 A/g	Supercapacitor	[94]
Canola waste	poly-orthoaminophenol/functionalized graphene oxide/activated canola waste	1350.5 F/g at 2.0 A/g	Supercapacitor	[95]
Coconut coir	$NiFe_2O_4$/reduced graphene oxide	599.9 F/g at 1.0 A/g	Supercapacitor	[96]
Potato peels	potato peels biochar/copper phthalocyanine	237.0 F/g at 6.1 A/g	Supercapacitor	[97]
Coconut shell	Coconut shell activated carbon/NiO	142.0 F/g at 6 mA/g	Supercapacitor	[98]
Coconut shell	Polyaniline/activated carbon/copper ferrite	248.3 F/g at 1.0 A/g	Supercapacitor	[99]
Wheat husk	$NiCo_2S_4$/wheat husk activated carbon	1962.0 F/g at 1.0 A/g		[100]
Rice husk	P,N-doped carbon/SiO_x	622 mA/g at 1.0 A.g after 1000 cycles	LiIB	[101]
Rice husk	S,N-doped carbon/SiO_x	632 mA/g at 1.0 A/g after 1200 cycles	NaIB	[102]
Wheat husk	Sulfur/carbon	822 mA/g at 0.2 C after 100 cycles	NaSB	[103]
Sugarcane bagasse	N,S,O-doped activated carbon	574 mA/g after 1000 cycles	LiIB/LiSB	[104]
Waste tea	Sulfur/activated carbon	428 mA/g at 0.5 C after 100 cycles	LiSB	[105]
Rice husk	Activated carbon/silicon	429 at 100 mA/g after 100 cycles	LiIB	[106]

Continuous effort to improve the electrochemical performance, cost, and environmental hazards is on-going in the materials research community. Very recently, Bigdeloo et al., prepared activated carbon from fennel flower waste as efficient and sustainable source of carbon, the activated carbon was further combined with functionalized graphene oxide to form a binary nanocomposite. A very thin layer of poly-orthoaminophenol was coated on the binary nanocomposite to obtain a ternary nanocomposite of poly-orthoaminophenol/functionalized graphene oxide/activated carbon from fennel flower. Electrochemical measurements were conducted on the ternary nanocomposite material formed using cyclic voltammetry (CV), galvanostatic charge-discharge (GCD), and electrochemical impedance spectroscopy (EIS) to evaluate the energy storage behavior of the electrode material. The ternary nanocomposite shows a specific capacitance of 1400.2 F/g at a current density of 2.0 A g^{-1}, capacity retention of 94.4% after 5000 cycles. Brunauer–Emmett–Teller (BET) analysis also reveal that the nanocomposite possesses a specific surface area of 2199.2 m^2 g^{-1} [92]. In a similar report, a nanocomposite was prepared from rice husk-activated carbon and silicon nanocrystals by calcination and magnesiothermic reduction process as depicted in Figure 4 (i), to obtain activated carbon-decorated silicon nanocrystals. The composite exhibited an aggregated structure of activated carbon encapsulated nanocrystalline silicon spheres, showing a high specific surface area of 498.5 m^2 g^{-1}. The electrochemical performance of the electrode prepared from the composite was tested toward LiIB cell. The cyclic voltamogram of the electrode is given in Figure 3 (ii). The electrode exhibited high coulombic efficiency of 97.5%, discharge capacity of 716 mAh g^{-1}, and high reversible specific capacity of 429 mAh g^{-1} after 100 cycles [106].

In another report, activated carbon binary composite was prepared from waste olive and date pits, and a ternary composite from olive, date, and sugar. The electrochemical performance of the composites was evaluated and the results showed that the Olive-Date activated carbon composite exhibits a specific capacitance of 104.1 F g^{-1} at 0.3 A g^{-1} with specific energy of 17.56 Wh Kg^{-1}. Meanwhile, the ternary composite (Olive/Date/Sugar) demonstrated better electrochemical performance with specific capacitance of 528 F g^{-1} at

0.3 A g^{-1} energy density of 36.82 Wh Kg^{-1} with high stability after 10,000 charge-discharge cycles at 10 A g^{-1} and a capacitance retention of 89.6% [107]. Coconut shell-activated carbon was also used to prepare a ternary hybrid composite with polyaniline and copper ferrite (CuF) via oxidative polymerization. The electrode prepared from the composite demonstrated a specific capacitance of 248.3 F g^{-1}, energy density of 49.66 Wh Kg^{-1} at 1.0 A g^{-1}, and at a maximum power density of 5996.6 W Kg^{-1} at 20 A g^{-1} in a two-electrode system. It also shows excellent capacitance retention of 92.8% after 2500 cycles which is an indication for a good cycle stability [99].

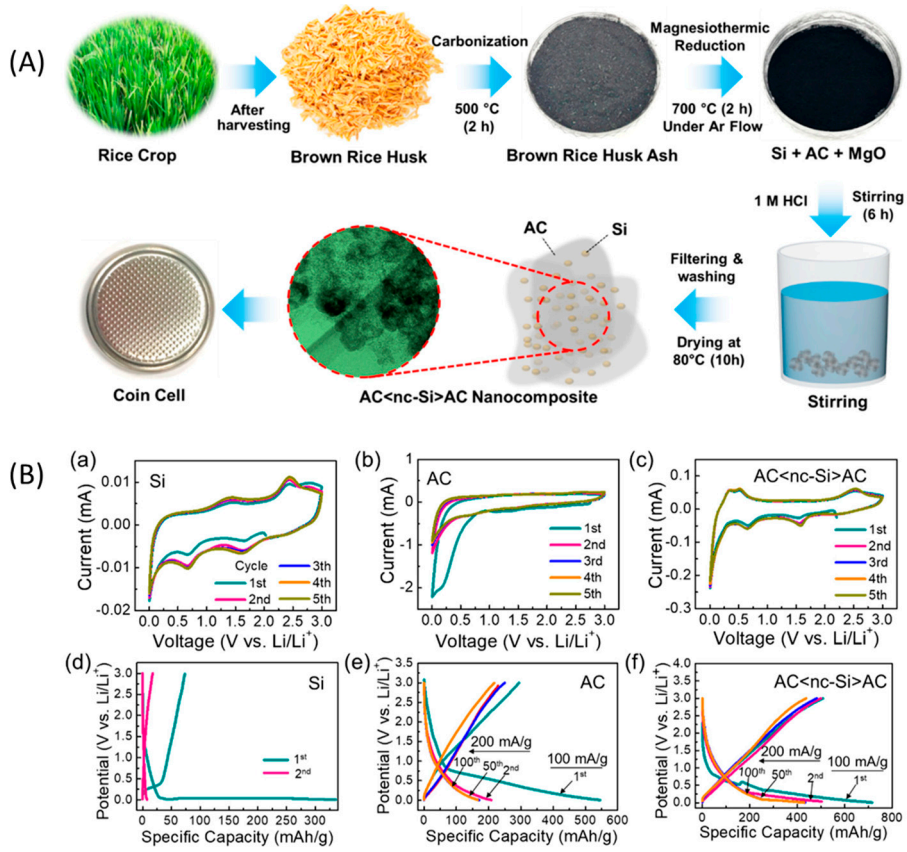


Figure 4. (**A**) Preparation of activated carbon/silicon nanocrystals composite materials and (**B**) cyclic voltammetry and galvanostatic charge–discharge (GCD) curves of the materials prepared. Adapted from MDPI [106].

6. Conclusions/Future Perspective

Transforming wastes, particularly biowaste materials from bioprocessing industries into useful resources, which can be applied directly or used as raw materials for other industrial processes is a fast-growing research challenge. Biowastes such as rice husk, sugarcane bagasse, nutshell, and wheat husk are rich in carbon and are therefore excellent precursors for the synthesis of varieties of carbon materials such as activated carbon, graphene, carbon nanotubes. Different conversion or synthesis methods such as pyrolysis, activation, and hydrothermal treatments among others have been applied by researchers to convert biowastes into different value-added carbon materials. From recent research reports, carbon materials from biowastes possess high surface area with high porosity which are essential for electrochemical and adsorption performance. Moreover, they can be doped with heteroatoms such as N, P, and S to enhance their electrocatalytic performance. Continuous improvement on the conversion of biowastes into value-added carbon materials will offer a safe and environmentally friendly alternative for waste disposal.

Waste residues such as corn starch, coconut shells, rice husk, coffee grounds, grape seeds, and apple pomace have shown promising properties as precursors for anodes in

LiIB and NaIB technologies, obtaining capacities up to 1125 mA h g^{-1} at 100 mA g^{-1} for the anode. In addition to this, the preparation of conductive carbon nanomaterials derived from biowaste results as a very appealing approach to improve the performance of the cathodes, in particular for the case of aqueous Zn-S batteries that are a low-cost and safer approach in comparison to other technologies.

Due to their working principle, the conversion of biowaste into high-surface-area carbon materials and nanomaterials seems a promising approach to decrease the cost in supercapacitors, where the treatment used has a direct impact on the surface area and hence in the capacitance and power density of the device. At the same time, when quality electrode materials that can perform excellently in energy storage devices are prepared from cheap biowaste-based carbon materials, the overall cost of the energy storage system will reduce, and it will be affordable by a common man.

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References

1. Guo, L.; Hu, Y.; Lei, Y.; Wu, H.; Yang, G.; Wang, Y.; Wei, G. Vitrification of petrochemical sludge for rapid, facile, and sustainable fixation of heavy metals. *J. Environ. Chem. Eng* **2022**, *10*, 108812. [CrossRef]
2. Sharifikolouei, E.; Ferraris, M. Potential role of vitrification and waste vitrification in the circular economy. In *Ceramics, Glass and Glass-Ceramics*; Baino, F., Tomalino, M., Tulyaganov, D., Eds.; PoliTO Springer Series; Springer: Cham, Switzerland, 2021. [CrossRef]
3. Dávalos, J.; Bonilla, A.; Villaquirán-Caicedo, M.A.; Gutiérrez, R.M.; Rincón, J.M. Preparation of glass-ceramic materials from coal ash and rice husk ash: Microstructural, physical and mechanical properties. *Céram. Vidr.* **2021**, *60*, 183–193. [CrossRef]
4. Singh, P.; Bhargava, C.; Kumar, M.; Singh, A.; Singh, P.K.; Kumar, P.; Sachdeva, A. Extraction and comparative study of green energy using different types of biowaste material. *Mater. Today Proc.* **2021**, *49*, 3474–3481. [CrossRef]
5. Siddiqui, O.; Dincer, I. Sustainable utilization of agricultural bio-waste for multigeneration of electricity, heating, cooling and freshwater. *J. Clean. Prod.* **2021**, *319*, 128540. [CrossRef]
6. Kumar, M.; Rai, D.; Bhardwaj, G.; Upadhyay, S.N.; Mishra, P.K. Pyrolysis of peanut shell: Kinetic analysis and optimization of thermal degradation process. *J. Ind. Crops Prod.* **2021**, *174*, 114128. [CrossRef]
7. Ajala, E.O.; Ighalo, J.O.; Ajala, M.A.; Adeniyi, A.G.; Ayanshola, A.M. Sugarcane bagasse: A biomass sufficiently applied for improving global energy, environment and economic sustainability. *J. Bioresour. Bioprocess.* **2021**, *8*, 87. [CrossRef]
8. Johnson, K.; Liu, Y.; Lu, M. A Review of Recent Advances in Spent Coffee Grounds Upcycle Technologies and Practices. *Front. Chem. Eng.* **2022**, *4*, 838605. [CrossRef]
9. Rachwał, K.; Waśko, A.; Gustaw, K.; Polak-Berecka, M. Utilization of brewery wastes in food industry. *PeerJ* **2020**, *8*, e9427. [CrossRef]
10. Younes, Y.A.; Kospa, D.A.; Salama, R.S.; Ahmed, A.I.; Ibrahim, A.A. Hydrophilic Candle Wastes Microcapsules as a Thermal Energy Storage Material for All-Day Steam and Electricity Cogeneration. *Desalination* **2023**, *550*, 116377. [CrossRef]
11. Elimelech, M. The Global Challenge for Adequate and Safe Water. *J. Water Supply Res. Technol.-AQUA* **2006**, *55*, 3–10. [CrossRef]
12. Werber, J.R.; Osuji, C.O.; Elimelech, M. Materials for Next-Generation Desalination and Water Purification Membranes. *Nat. Rev. Mater.* **2016**, *1*, 16018. [CrossRef]
13. Bakry, A.M.; Alamier, W.M.; Salama, R.S.; Samy El-Shall, M.; Awad, F.S. Remediation of Water Containing Phosphate Using Ceria Nanoparticles Decorated Partially Reduced Graphene Oxide (CeO_2-PRGO) Composite. *Surf. Interfaces* **2022**, *31*, 102006. [CrossRef]
14. Wu, X.; Tian, Z.; Guo, J. A review of the theoretical research and practical progress of carbon neutrality. *J. Sustain. Oper. Comput.* **2022**, *3*, 54–66. [CrossRef]
15. González, F.J.; Montesinos, A.; Araujo-Morera, J.; Verdejo, R.; Hoyos, M. 'In-Situ' Preparation of Carbonaceous Conductive Composite Materials Based on PEDOT and Biowaste for Flexible Pseudocapacitor Application. *J. Compos. Sci.* **2020**, *4*, 87. [CrossRef]
16. Sundriyal, S.; Shrivastav, V.; Kaur, A.; Dubey, P.; Mishra, S.; Deep, A.; Dhakate, S. Waste Office Papers as a Cellulosic Material Reservoir to Derive Highly Porous Activated Carbon for Solid-State Electrochemical Capacitor. *IEEE Trans. Nanotechnol.* **2021**, *20*, 481–488. [CrossRef]

17. Genovese, M.; Wu, H.; Virya, A.; Li, J.; Shen, P.; Lian, K. Ultrathin all-solid-state supercapacitor devices based on chitosan activated carbon electrodes and polymer electrolytes. *Electrochim. Acta* **2018**, *273*, 392–401. [CrossRef]
18. Karnan, M.; Subramani, K.; Srividhya, P.K.; Sathish, M. Electrochemical Studies on Corncob Derived Activated Porous Carbon for Supercapacitors Application in Aqueous and Non-aqueous Electrolytes. *J. Electrochim.* **2017**, *228*, 586–596. [CrossRef]
19. Maharjan, M.; Bhattarai, A.; Ulaganathan, M.; Wai, N.; Ohnmar, M.; Wang, J.; Mariana, T. High surface area bio-waste based carbon as a superior electrode for vanadium redox flow battery. *J. Power Sources* **2017**, *362*, 50–56. [CrossRef]
20. Tavasoli, A.; Aslan, M.; Salimi, M.; Balou, S.; Pirbazari, S.M.; Hashemi, H.; Kohansal, K. Influence of the blend nickel/porous hydrothermal carbon and cattle manure hydrochar catalyst on the hydrothermal gasification of cattle manure for H_2 production. *J. Energy Convers. Manag.* **2018**, *173*, 15–28. [CrossRef]
21. Zhang, Y.; Gao, Z.; Song, N.; Li, X. High-performance supercapacitors and batteries derived from activated banana-peel with porous structures. *Electrochim. Acta* **2016**, *222*, 1257–1266. [CrossRef]
22. Charoensook, K.; Huang, C.L.; Tai, H.C.; Lanjapalli, V.V.K.; Chiang, L.M.; Hosseini, S.; Lin, Y.T.; Li, Y.Y. Preparation of Porous Nitrogen-Doped Activated Carbon Derived from Rice Straw for High-Performance Supercapacitor Application. *J. Taiwan Inst. Chem. Eng.* **2021**, *120*, 246–256. [CrossRef]
23. Saeed, A.A.H.; Harun, N.Y.; Bilad, M.R.; Afzal, M.T.; Parvez, A.M.; Roslan, F.A.S.; Rahim, S.A.; Vinayagam, V.D.; Afolabi, H.K. Moisture content impact on properties of briquette produced from rice husk waste. *Sustainability* **2021**, *13*, 3069. [CrossRef]
24. Ullah, H.; Lun, L.; Riaz, L.; Naseem, F.; Shahab, A.; Rashid, A. Physicochemical characteristics and thermal degradation behavior of dry and wet torrefied orange peel obtained by dry/wet torrefaction. *Biomass Convers. Biorefinery* **2021**. [CrossRef]
25. Menon, S.D.; Sampath, K.; Kaarthik, S.S. Feasibility studies of coconut shells biomass for downdraft gasification. *Mater. Today Proc.* **2021**, *44*, 3133–3137. [CrossRef]
26. Camargo, J.M.O.; Gallego-Ríos, J.M.; Neto, A.M.P.; Antonio, G.C.; Modesto, M.; Leite, J.T.C. Characterization of sugarcane straw and bagasse from dry cleaning system of sugarcane for cogeneration system. *J. Renew. Energy* **2020**, *158*, 500–508. [CrossRef]
27. Kluska, J.; Ochnio, M.; Kardaś, D. Carbonization of corncobs for the preparation of barbecue charcoal and combustion characteristics of corncob char. *J. Waste Manag.* **2020**, *105*, 560–565. [CrossRef]
28. Coronado, M.A.; Montero, G.; Montes, D.G.; Valdez-Salas, B.; Ayala, J.R.; García, C.; Carrillo, M.; León, J.A.; Moreno, A. Physicochemical characterization and SEM-EDX analysis of brewer's spent grain from the craft brewery industry. *Sustainability* **2020**, *12*, 7744. [CrossRef]
29. Sarkar, J.K.; Wang, Q. Characterization of pyrolysis products and kinetic analysis of waste jute stick biomass. *Processes* **2020**, *8*, 837. [CrossRef]
30. Wang, S.; Nam, H.; Nam, H. Preparation of activated carbon from peanut shell with KOH activation and its application for H_2S adsorption in confined space. *J. Environ. Chem. Eng.* **2020**, *8*, 103683. [CrossRef]
31. Barbanera, M.; Muguerza, I.F. Effect of the temperature on the spent coffee grounds torrefaction process in a continuous pilot-scale reactor. *Fuel* **2020**, *262*, 116493. [CrossRef]
32. Tahir, M.H.; Zhao, Z.; Ren, J.; Rasool, T.; Naqvi, S.R. Thermo-kinetics and gaseous product analysis of banana peel pyrolysis for its bioenergy potential. *Biomass Bioenergy* **2019**, *122*, 193–201. [CrossRef]
33. Nieto, N.; Noya, O.; Iturrondobeitia, A.; Sanchez-Fontecoba, P.; Pérez-López, U.; Palomares, V.; Lopez-Urionabarrenechea, A.; Rojo, T. On the Road to Sustainable Energy Storage Technologies: Synthesis of Anodes for Na-Ion Batteries from Biowaste. *Batteries* **2022**, *8*, 28. [CrossRef]
34. Rodriguez Ortiz, L.; Torres, E.; Zalazar, D.; Zhang, H.; Rodriguez, R.; Mazza, G. Influence of pyrolysis temperature and bio-waste composition on biochar characteristics. *J. Renew. Energy* **2020**, *155*, 837–847. [CrossRef]
35. Al, A.; Meltem, R. High-performance nanostructured bio-based carbon electrodes for energy storage applications. *Cellulose* **2021**, *28*, 5169–5218. [CrossRef]
36. Bian, R.; Shi, W.; Luo, J.; Li, W.; Wang, Y.; Joseph, S.; Gould, H.; Zheng, J.; Zhang, X.; Liu, X.; et al. Copyrolysis of food waste and rice husk to biochar to create a sustainable resource for soil amendment: A pilot-scale case study in Jinhua, China. *J. Clean. Prod.* **2022**, *347*, 131269. [CrossRef]
37. Bai, X.; Wang, Z.; Luo, J.; Wu, W.; Liang, Y.; Tong, X.; Zhao, Z. Hierarchical Porous Carbon with Interconnected Ordered Pores from Biowaste for High-Performance Supercapacitor Electrodes. *Nanoscale Res. Lett.* **2020**, *15*, 88. [CrossRef]
38. Jung, S.; Myung, Y.; Kim, B.N.; Kim, I.G.; You, I.; Kim, T. Activated Biomass-derived Graphene-based Carbons for Supercapacitors with High Energy and Power Density. *Sci. Rep.* **2018**, *8*, 1915. [CrossRef]
39. Reza, M.T.; Lynam, J.G.; Uddin, M.H.; Coronella, C.J. Hydrothermal carbonization: Fate of inorganics. *Biomass Bioenergy* **2013**, *49*, 86–94. [CrossRef]
40. Liu, X.; Zhang, S.; Wen, X.; Chen, X.; Wen, Y.; Shi, X.; Mijowska, E. High yield conversion of biowaste coffee grounds into hierarchical porous carbon for superior capacitive energy storage. *Sci. Rep.* **2020**, *10*, 3518. [CrossRef]
41. Heidarinejad, Z.; Dehghani, M.H.; Heidari, M.; Javedan, G.; Ali, I.; Sillanpää, M. Methods for preparation and activation of activated carbon: A review. *J. Environ. Chem. Lett.* **2020**, *18*, 393–415. [CrossRef]
42. Tobi, A.R.; Dennis, J.O. Activated carbon from composite of palm bio-waste as electrode material for solid-state electric double layer capacitor. *J. Energy Storage* **2021**, *42*, 103087. [CrossRef]

43. Jiang, X.; Guo, F.; Jia, X.; Liang, S.; Peng, K.; Qian, L. Synthesis of biomass-based porous graphitic carbon combining chemical treatment and hydrothermal carbonization as promising electrode materials for supercapacitors. *Ionics* **2020**, *26*, 3655–3668. [CrossRef]
44. Patel, P.S.; Bandre, N.; Saraf, A.; Ruparelia, J.P. Electro-catalytic materials (electrode materials) in electrochemical wastewater treatment. *Procedia Eng.* **2013**, *51*, 430–435. [CrossRef]
45. An, H.; Cui, H.; Zhang, W.; Zhai, J.; Qian, Y.; Xie, X.; Li, Q. Fabrication and electrochemical treatment application of a microstructured TiO_2-NTs/Sb-SnO_2/PbO_2 anode in the degradation of C.I. Reactive Blue 194 (RB 194). *Chem. Eng. J.* **2012**, *209*, 86–93. [CrossRef]
46. Ma, Z.; Wang, K.; Qiu, Y.; Liu, X.; Cao, C.; Feng, Y.; Hu, P. Nitrogen and sulfur co-doped porous carbon derived from biowaste as a promising electrocatalyst for zinc-air battery. *Energy* **2017**, *143*, 43–55. [CrossRef]
47. Zhang, J.; Qu, L.; Shi, G.; Liu, J.; Chen, J.; Dai, L. N,P-Codoped Carbon Networks as Efficient Metal-free Bifunctional Catalysts for Oxygen Reduction and Hydrogen Evolution Reactions. *Zuschriften Angew.* **2016**, *250100*, 2270–2274. [CrossRef]
48. Ţurcanu, A.A.; Matei, E.; Râpă, M.; Predescu, A.M.; Coman, G.; Predescu, C. Biowaste Valorization Using Hydrothermal Carbonization for Potential Wastewater Treatment Applications. *Water* **2022**, *14*, 2344. [CrossRef]
49. Gan, L.; Wu, Y.; Song, H.; Zhang, S.; Lu, C.; Yang, S.; Wang, Z.; Jiang, B.; Wang, C.; Li, A. Selective removal of nitrate ion using a novel activated carbon composite carbon electrode in capacitive deionization. *Sep. Purif. Technol.* **2019**, *212*, 728–736. [CrossRef]
50. Li, H.; Dong, X.; da Silva, E.B.; de Oliveira, L.M.; Chen, Y.; Ma, L.Q. Mechanisms of metal sorption by biochars: Biochar characteristics and modifications. *Chemosphere* **2017**, *178*, 466–478. [CrossRef]
51. Lu, Y.; Zhang, Q.; Chen, J. Recent progress on lithium-ion batteries with high electrochemical performance. *Sci. China Chem.* **2019**, *62*, 533–548. [CrossRef]
52. Sangprasert, T.; Sattayarut, V.; Rajrujithong, C.; Khanchaitit, P.; Khemthong, P.; Chanthad, C.; Grisdanurak, N. Making use of the inherent nitrogen content of spent coffee grounds to create nanostructured activated carbon for supercapacitor and lithium-ion battery applications. *Diam. Relat. Mater.* **2022**, *127*, 109164. [CrossRef]
53. Thanwisai, P.; Chaiyapo, N.; Phuenhinlad, P.; Kanaphan, Y.; Nash, J.; Chotsuwan, C.; Klamchuen, A.; Wang, Y.; Nann, T.; Meethong, N. Mesoporous and defective activated carbon cathode for $AlCl_4^-$ anion storage in non-aqueous aluminium-ion batteries. *Carbon* **2022**, *191*, 195–204. [CrossRef]
54. Liu, S.-F.; Kuo, C.-H.; Lin, H.-Y.; Lu, C.-Z.; Kang, J.-W.; Fey, G.T.-K.; Chen, H.-Y. Biowaste-derived Si@SiOx/C anodes for sustainable lithium-ion batteries. *Electrochim. Acta* **2022**, *403*, 139580. [CrossRef]
55. Han, X.R.; Guo, X.T.; Xu, M.J.; Pang, H.; Ma, Y.W. Clean Utilization of Palm Kernel Shell: Sustainable and Naturally Heteroatom-Doped Porous Activated Carbon for Lithium–Sulfur Batteries. *Rare Met.* **2020**, *39*, 1099–1106. [CrossRef]
56. Rybarczyk, M.K.; Li, Y.; Qiao, M.; Hu, Y.S.; Titirici, M.M.; Lieder, M. Hard Carbon Derived from Rice Husk as Low Cost Negative Electrodes in Na-Ion Batteries. *J. Energy Chem.* **2019**, *29*, 17–22. [CrossRef]
57. Mauger, A.; Julien, C.M. Critical review on lithium-ion batteries: Are they safe? Sustainable? *Ionics* **2017**, *23*, 1933–1947. [CrossRef]
58. Amatucci, G.G.; Tarascon, J.M.; Klein, L.C. CoO_2, the end member of the Li_xCoO_2 Solid Solution. *J. Electrochem. Soc.* **1996**, *143*, 1114–1123. [CrossRef]
59. Nanaji, K. Jute sticks derived novel graphitic porous carbon nanosheets as Li-ion battery anode material with superior electrochemical properties. *Int. J. Energy Res.* **2019**, *44*, 2289–2297. [CrossRef]
60. Kwon, H.J.; Hwang, J.; Shin, H.; Jeong, M.; Chung, K.Y.; Sun, Y.; Jung, H. Nano/Microstructured Silicon−Carbon Hybrid Composite Particles Fabricated with Corn Starch Biowaste as Anode Materials for Li-Ion Batteries. *Nano Lett.* **2020**, *20*, 625–635. [CrossRef] [PubMed]
61. Wang, Q.; Zhu, X.; Liu, Y.; Fang, Y.; Zhou, X.; Bao, J. Rice husk-derived hard carbons as high-performance anode materials for sodium-ion batteries. *Carbon.* **2018**, *127*, 658–666. [CrossRef]
62. Barnes, P.; Smith, K.; Parrish, R.; Jones, C.; Skinner, P.; Storch, E.; White, Q.; Deng, C.; Karsann, D.; Lau, M.L.; et al. A Non-Aqueous Sodium Hexafluorophosphate-Based Electrolyte Degradation Study: Formation and Mitigation of Hydrofluoric Acid. *J. Power Sources* **2020**, *447*, 227363. [CrossRef]
63. Ould, D.M.C.; Menkin, S.; O'Keefe, C.A.; Coowar, F.; Barker, J.; Grey, C.P.; Wright, D.S. New Route to Battery Grade NaPF6 for Na-Ion Batteries: Expanding the Accessible Concentration. *Angew. Chem.-Int. Ed.* **2021**, *60*, 24882–24887. [CrossRef]
64. Landesfeind, J.; Hosaka, T.; Graf, M.; Kubota, K.; Komaba, S.; Gasteiger, H.A. Comparison of Ionic Transport Properties of Non-Aqueous Lithium and Sodium Hexafluorophosphate Electrolytes. *J. Electrochem. Soc.* **2021**, *168*, 040538. [CrossRef]
65. Walter, M.; Kovalenko, M.V.; Kravchyk, K.V. Challenges and benefits of post-lithium-ion batteries. *New J. Chem.* **2020**, *44*, 1677–1683. [CrossRef]
66. Lv, W.; Wen, F.; Xiang, J.; Zhao, J.; Li, L.; Wang, L.; Liu, Z.; Tian, Y. Peanut shell derived hard carbon as ultralong cycling. *Electrochim. Acta* **2015**, *176*, 533–541. [CrossRef]
67. Zhang, S.; Li, Y.; Li, M.I.N. Porous Hard Carbon Derived from Walnut Shell as an Anode Material for Sodium-Ion Batteries. *JOM* **2018**, *70*, 1387–1391. [CrossRef]
68. Demir, E.; Aydin, M.; Andreas, A.; Demir-cakan, R. Apricot shell derived hard carbons and their tin oxide composites as anode materials for sodium-ion batteries. *J. Alloys Compd.* **2019**, *788*, 1093–1102. [CrossRef]
69. Wu, L.; Buchholz, D.; Vaalma, C.; Giffin, G.A. Apple-Biowaste-Derived Hard Carbon as a Powerful Anode Material for Na-Ion Batteries. *ChemElectroChem* **2016**, *3*, 292–298. [CrossRef]

70. Zhang, X.; Wang, X.; Xie, Z.; Zhou, Z. Recent progress in rechargeable alkali metal-air batteries. *Green Energy Environ.* **2016**, *1*, 4–17. [CrossRef]
71. Li, Y.; Lu, J. Metal—air Batteries: Will They Be the Future Electrochemical Energy Storage Device of choice? *Energy Lett.* **2017**, *2*, 1370–1377. [CrossRef]
72. Zhang, J. A metal-free bifunctional electrocatalyst for oxygen reduction and oxygen evolution reactions. *Nat. Nanotechnol.* **2015**, *10*, 444–452. [CrossRef] [PubMed]
73. Li, Y.; Wang, Z.; Cai, Y.; Pam, M.E.; Yang, Y.; Zhang, D.; Wang, Y.; Huang, S. Designing Advanced Aqueous Zinc-Ion Batteries: Principles, Strategies, and Perspectives. *Energy Environ. Mater.* **2022**, *5*, 823–851. [CrossRef]
74. Li, W.; Wang, K.; Jiang, K. A Low Cost Aqueous Zn–S Battery Realizing Ultrahigh Energy Density. *Adv. Sci.* **2020**, *7*, 2000761. [CrossRef] [PubMed]
75. Mensah-darkwa, K.; Zequine, C.; Kahol, P.K.; Gupta, R.K. Supercapacitor Energy Storage Device Using Biowastes: A Sustainable Approach to Green Energy. *Sustainability* **2019**, *11*, 414. [CrossRef]
76. Mangisetti, S.R.; Kamaraj, M.; Sundara, R. Green Approach for Synthesizing Three Different Carbon Microstructures from a Single Biowaste Bombax malabaricum for Fully Biocompatible Flexible Supercapacitors and Their Performance in Various Electrolytes. *ACS Omega* **2019**, *4*, 6399–6410. [CrossRef]
77. Misnon, I.I.; Zain, N.K.M.; Lei, T.S.; Vijayan, B.L.; Jose, R. Activated carbon with graphitic content from stinky bean seedpod biowaste as supercapacitive electrode material. *Ionics* **2020**, *26*, 4081–4093. [CrossRef]
78. Hadjipaschalis, I.; Poullikkas, A.; Efthimiou, V. Overview of current and future energy storage technologies for electric power applications. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1513–1522. [CrossRef]
79. Al-Thabaiti, S.A.; Mostafa, M.M.M.; Ahmed, A.I.; Salama, R.S. Synthesis of Copper/Chromium Metal Organic Frameworks-Derivatives as an Advanced Electrode Material for High-Performance Supercapacitors. *Ceram. Int.* **2023**, *49*, 5119–5129. [CrossRef]
80. Samantara, A.K.; Ratha, S. Components of Supercapacitor BT. In *Materials Development for Active/Passive Components of a Supercapacitor: Background, Present Status and Future Perspective*; Briefs in Materials; Spinger: Berlin/Heidelberg, Germany, 2018; pp. 11–39. [CrossRef]
81. Wan, L.; Chen, D.; Liu, J.; Zhang, Y.; Chen, J.; Du, C.; Xie, M. Facile preparation of porous carbons derived from orange peel via basic copper carbonate activation for supercapacitors. *J. Alloys Compd.* **2020**, *823*, 153747. [CrossRef]
82. Selvaraj, A.R.; Muthusamy, A.; Cho, I.; Kim, H.-J.; Senthil, K.; Prabakar, K. Ultrahigh surface area biomass derived 3D hierarchical porous carbon nanosheet electrodes for high energy density supercapacitors. *Carbon* **2021**, *174*, 463–474. [CrossRef]
83. Song, Y.; Qu, W.; He, Y.; Yang, H.; Du, M.; Wang, A.; Yang, Q.; Chen, Y. Synthesis and processing optimization of N-doped hierarchical porous carbon derived from corncob for high performance supercapacitors. *J. Energy Storage* **2020**, *32*, 101877. [CrossRef]
84. Surya, K.; Michael, M.S. Hierarchical porous activated carbon prepared from biowaste of lemon peel for electrochemical double layer capacitors. *Biomass Bioenergy* **2021**, *152*, 106175. [CrossRef]
85. Li, C.; Chen, H.; Zhang, L.; Jiao, S.; Zhang, H.; Zhang, J.; Li, P.; Tao, Y.; Zhao, X. Rice hull-derived carbon for supercapacitors: Towards sustainable silicon-carbon supercapacitors. *Polymers* **2021**, *13*, 4463. [CrossRef] [PubMed]
86. Shah, S.S.; Cevik, E.; Aziz, M.A.; Qahtan, T.F.; Bozkurt, A.; Yamani, Z.H. Jute Sticks Derived and Commercially Available Activated Carbons for Symmetric Supercapacitors with Bio-electrolyte: A Comparative Study. *J. Synth. Met.* **2021**, *277*, 116765. [CrossRef]
87. Hsieh, T.-H.; Wang, H.-L.; Yu, G.-T.; Huang, G.-M.; Lin, J.-H. Meso-pore dominant activated carbon from spent coffee grounds for high-performance electrochemical capacitors in organic electrolyte. *J. Environ. Chem. Eng.* **2021**, *9*, 106418. [CrossRef]
88. Taer, E.; Yusra, D.A.; Amri, A.; Awitdrus; Taslim, R.; Apriwandi; Agustino; Putri, A. Synthesis of activated carbon made from banana stem fibers as the supercapacitor electrodes. *Mater. Today Proc.* **2020**, *44*, 3346–3349. [CrossRef]
89. Lee, K.C.; Lim, M.S.W.; Hong, Z.Y.; Chong, S.; Tiong, T.J.; Pan, G.T.; Huang, C.M. Coconut shell-derived activated carbon for high-performance solid-state supercapacitors. *Energies* **2021**, *14*, 4546. [CrossRef]
90. Xu, M.; Wang, A.; Xiang, Y.; Ejaz, A.; Niu, J. Self-template bagasse-based porous carbons for high performance supercapacitors. *J. Ind. Crops Prod.* **2022**, *176*, 114291. [CrossRef]
91. Saini, S.; Chand, P.; Joshi, A. Biomass derived carbon for supercapacitor applications: Review. *J. Energy Storage* **2021**, *39*, 102646. [CrossRef]
92. Bigdeloo, M.; Kowsari, E.; Ehsani, A.; Ramakrishna, S.; Chinnappan, A. Activated carbon derived from fennel flower waste as high-efficient sustainable materials for improving cycle stability and capacitance performance of electroactive nanocomposite of conductive polymer. *J. Energy Storage* **2022**, *55*, 105793. [CrossRef]
93. Okenwa, C.; Aigbodion, V.S.; Offor, P.O.; Onoh, E.U. New insights into improved electrochemical performance of graphene synthesized from rice husk doped graphite composite electrode for supercapacitor. *Chem. Data Collect.* **2021**, *40*, 100887. [CrossRef]
94. Ye, W.; Cai, J.; Yu, F.; Li, X.; Wang, X. Nitrogen-doped bagasse carbon spheres/graphene composite for high-performance supercapacitors. *Biomass Bioenergy* **2021**, *145*, 105949. [CrossRef]
95. Bigdeloo, M.; Kowsari, E.; Ehsani, A.; Chinnappan, A.; Ramakrishna, S. Functionalized graphene oxide/activated carbon from canola waste as sustainable nanomaterials to improve pseudocapacitance performance of the electroactive conductive polymer. *J. Energy Storage* **2022**, *50*, 104279. [CrossRef]

96. Tamilselvi, R.; Lekshmi, G.S.; Padmanathan, N.; Selvarage, V.; Bazaka, O.; Levchenko, I.; Bazaka, K.; Mandhakini, M. $NiFe_2O_4$/rGO nancomposites produced by soft bubble assembly for energy storage and environmental remediation. *Renew. Energy* **2022**, *181*, 1386–1401. [CrossRef]
97. Wesley, R.J.; Durairaja, A.; Ramanathan, S.; Obadiah, A.; Justinabraham, R.; Lv, X.; Vasanthkumar. Potato peels biochar composite with copper phthalocyanine for energy storage application. *Diam. Relat. Mater.* **2021**, *115*, 108360. [CrossRef]
98. Ramos, M.O.; Meraz, E.D.A.; Rojo, J.M.; Pacheco-Catalán, D.E.; Castro, M.A.P.; Ortiz, R.S.M. Activated carbons from coconut shell and NiO-based composites for energy storage systems. *J. Mater Sci. Mater. Electron.* **2021**, *32*, 4872–4884. [CrossRef]
99. Pandey, V.K.; Verma, S.; Verma, B. Polyaniline/activated carbon/copper ferrite (PAN/AC/CuF) based ternary composite as an efficient electrode material for supercapacitor. *Chem. Phys. Lett.* **2022**, *802*, 139780. [CrossRef]
100. Baig, M.M.; Gul, I.H. Transformation of Wheat Husk to 3D Activated Carbon/NiCo2S4 Frameworks for High-Rate Asymmetrical Supercapacitors. *J. Energy Storage* **2021**, *37*, 102477. [CrossRef]
101. Zhang, H.; Zhang, N.; Man, J.; Du, Y.; Cui, J.; Sun, J. A Sustainable Approach from Rice Husks to P,N-Dual Doping Porous C/SiOx Composites for High-Performance Lithium-Ion Battery Anodes. *J. Electroanal. Chem.* **2022**, *904*, 115939. [CrossRef]
102. Cui, J.; Qiu, Y.; Zhang, H.; Yao, Z.; Zhao, W.; Liu, Y.; Sun, J. Sulfur- and Nitrogen-Doped Rice Husk-Derived C/SiOx Composites as High-Performance Lithium-Ion Battery Anodes. *Solid State Ion.* **2021**, *361*, 115548. [CrossRef]
103. Zhao, D.; Ge-Zhang, S.; Zhang, Z.; Tang, H.; Xu, Y.; Gao, F.; Xu, X.; Liu, S.; Zhou, J.; Wang, Z.; et al. Three-Dimensional Honeycomb-Like Carbon as Sulfur Host for Sodium–Sulfur Batteries without the Shuttle Effect. *ACS Appl. Mater. Interfaces* **2022**, *14*, 54662–54669. [CrossRef] [PubMed]
104. Bosubabu, D.; Sampathkumar, R.; Karkera, G.; Ramesha, K. Facile Approach to Prepare Multiple Heteroatom-Doped Carbon Material from Bagasse and Its Applications toward Lithium-Ion and Lithium−sulfur Batteries. *Energy Fuels* **2021**, *35*, 8286–8294. [CrossRef]
105. Arie, A.A.; Kristianto, H.; Cengiz, E.C.; Demir-Cakan, R. Waste Tea-Based Porous Carbon–Sulfur Composite Cathodes for Lithium–Sulfur Battery. *Ionics* **2020**, *26*, 201–212. [CrossRef]
106. Sekar, S.; Ahmed, T.A.; Inamdar, A.I.; Lee, Y.; Im, H.; Kim, D.Y.; Lee, S. Activated Carbon-Decorated Spherical Silicon Nanocrystal Composites Synchronously-Derived from Rice Husks for Anodic Source of Lithium-Ion Battery. *Nanomaterials* **2019**, *9*, 1055. [CrossRef] [PubMed]
107. Azzou, K.A.K.; Terbouche, A.; Ramdane-Terbouche, C.A.; Belkhalfa, H.; Bachari, K.; Hauchard, D.; Mezaoui, D. Electrochemical performance of new hybrid activated carbon materials from binary and ternary Date-Olive pits for supercapacitor electrodes. *J. Energy Storage* **2022**, *47*, 103559. [CrossRef]