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## **Recent Advances in Food Waste-Derived Nanoporous Carbon for Energy Storage**

Jefrin M. Davidraj<sup>1</sup>, Clastinrusselraj Indirathankam Sathish<sup>1</sup>, Mercy Rose Benzigar<sup>1</sup>, Zhixuan Li<sup>1</sup>, Xiangwei Zhang<sup>1</sup>, Rohan Bahadur<sup>1</sup>, Kavitha Ramadass<sup>1</sup>, Gurwinder Singh<sup>1</sup>, Jiabao Yi<sup>1,\*</sup>, Prashant Kumar<sup>1,\*</sup> and Ajayan Vinu<sup>1,\*</sup>

<sup>1</sup>*Global Innovative Centre for Advanced Nanomaterials (GICAN), School of Engineering, College of Engineering, Science, and Environment, The University of Newcastle, Callaghan, New South Wales 2308, Australia*

**Correspondence E-mail:** [jiabao.yi@newcastle.edu.au](mailto:jiabao.yi@newcastle.edu.au),  
[prashant.kumar@newcastle.edu.au](mailto:prashant.kumar@newcastle.edu.au), [ajayan.vinu@newcastle.edu.au](mailto:ajayan.vinu@newcastle.edu.au)

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## **Abstract**

Affordable and environmentally friendly electrochemically active raw energy storage materials are in high demand to switch to mass-scale renewable energy. One particularly promising avenue is the feasibility of utilizing food waste-derived nanoporous carbon. This material holds significance due to its widespread availability, affordability, ease of processing, and, notably, its cost-free nature. Over the years, various strategies have been developed to convert different food wastes into nanoporous carbon materials with enhanced electrochemical properties. The electrochemical performance of these materials is influenced by both intrinsic factors, such as the composition of elements derived from the original food sources and recipes, and extrinsic factors, including the conditions during pyrolysis and activation. While current efforts are dedicated to optimizing process parameters to achieve superior performance in electrochemical energy storage devices, it is timely to take stock of the current state of research in this emerging field. This review provides a comprehensive overview of recent developments in the fabrication and surface characterisation of porous carbons from different food wastes. A special focus is given on the applications of these food waste derived porous carbons for energy storage applications including batteries and supercapacitors.

**Keywords:** Food waste, Energy storage, Nanoporous, Activation, Carbon

## 1. Introduction

Modern economies rely heavily on electricity, and this dependence is poised to soar with the increased electrification of remote regions like mountains, deserts, and forests, in addition to the already substantial urban electricity consumption.**[1]** Various sectors, ranging from heavy industries like steel plants and petrochemical refineries to small-scale industries such as textiles and plastics, as well as construction projects like buildings and bridges, and essential healthcare infrastructure, depend on a consistent electric supply. Within households, electricity is consumed by a wide array of devices, including handheld portable digital gadgets, electric kitchen appliances, and heating and air-conditioning systems. However, it's important to note that electricity usage is often associated with greenhouse gas emissions due to the generation of electricity using energy resources, especially fossil fuels. The combustion of fossil fuels, including coal, gas, and oil, is a primary source of CO<sub>2</sub> emissions, while these fossil fuels are only finite resources. Therefore, developing renewable energy sources using hydroelectric, nuclear, solar, wind power, hydrogen, supercapacitors and rechargeable batteries as the storage devices is critical and urgent because it offers a more sustainable and environmentally friendly way to meet our increasing energy demand.**[2-12]**

Thanks to the pioneering research of Nobel Prize laureate George Goodenough and the tremendous efforts of numerous research groups and laboratories worldwide, lithium-ion batteries (LIBs) have become ubiquitous in households.**[13]** Materials like LiFePO<sub>4</sub>, LiCoPO<sub>4</sub>, and LiNiPO<sub>4</sub> have been widely used in battery fabrication.**[14-16]** These innovations have resulted in the successful commercialization of LIBs.**[17-23]** However, given that lithium is not abundant, researchers have been exploring alternative materials. One of the most promising options is sodium (Na), which is

readily available in ocean water. Efforts are being made to realize the commercialization of sodium-ion batteries (SIBs).[24-28] Simultaneously, lithium-sulfur batteries (LSBs) have also made significant strides in development.[29] Moreover, recent research efforts have also been directed towards the commercialization of iron-ion, magnesium-ion, and aluminium-ion batteries.[30-32] Over the past few decades, not only have new battery materials been developed, but there has also been a strong emphasis on enhancing their power ratings and rate capabilities, making them suitable for heavy-duty applications such as electric vehicles and ensuring their long cycle life.[33,34]

On the other hand, supercapacitors represent a remarkable class of electrochemical energy storage devices, boasting energy storage capabilities that are often a hundred times greater than traditional batteries and an impressive charge and discharge rate that is ten times faster than conventional capacitors[12,35-38]. These supercapacitors find wide-ranging applications to meet emergency energy needs, power portable electronic devices, and support industrial power requirements.[39-41] It's worth noting that while batteries are renowned for their high energy density (energy generation capacity), supercapacitors excel in providing high power density (rapid energy delivery).[42] The optimization of cell design plays a crucial role in achieving a balance between high energy and power output. The performance of supercapacitors is primarily contingent on the characteristics and properties of the electrode materials, as well as the interactions between the electrodes and the electrolyte.[41,43-46] Among the various candidate materials, nanoporous carbon-based substances have proven to be the most promising for commercial supercapacitor applications. This preference stems from their flexibility in material design, encompassing factors like surface area, pore shape, and pore size

distribution, as well as their compatibility with economic production methods. Moreover, micro-, and nanoporous carbon materials, characterized by their structural, chemical, and thermal stability, exhibit markedly improved cyclability and rate capability. To further harness the advantages of both high energy and power density, battery-supercapacitor hybrid devices have been developed, consolidating these attributes into a single device.[47-49] Additionally, a wide array of inorganic materials, including metal oxides, sulphides, nitrides[50-52], carbides, fullerenes,[7,53-55]and phosphides, either alone or in conjunction with conducting organic polymers like polyaniline (PA), have been deployed in various energy generation and storage devices, diversifying the landscape of materials for these applications.[56-63]

While rechargeable batteries and supercapacitors are recognized for their potential to reduce emissions significantly, many of these technologies are burdened by high costs and raise environmental concerns when they come to disposal. As we shift our focus towards economically and environmentally sustainable solutions for powering household devices, vehicles, and even entire power grids, the innovation in the design of battery and supercapacitor materials becomes a critical driver, paving the way for renewable energy solutions that can stand the test of time. Scalability, reproducibility, high cost of production, device failure at high charge/discharge rate operation, and incapability in high load operation conditions are some of the challenges facing energy storage materials. Salient criteria for suitable energy storage materials therefore include facile synthesis at low cost in scalable and reproducible manner, high load as well as rate capability (especially in cyclic performance). Recycling the used energy storage materials can further be useful. Innovations in device fabrication can help the purpose as well.

Carbon-based materials have emerged as promising energy storage materials candidates in this pursuit.[8-11,45,64-67] They offer the advantage of easy recyclability as they can be converted back into precursor forms, making them an attractive option for environmentally conscious researchers. Carbon, the fundamental building block of all plants and living organisms, is primarily composed of hydrocarbons, making it an excellent choice for energy generation and storage materials. This is a topic that has garnered significant attention, as evidenced by several relevant reviews in the field.[68-71] As the demand for energy generation and storage devices continues to surge, the economic aspect of material systems becomes increasingly crucial. Low-cost materials that are readily available and can be processed without the use of harsh chemicals are highly preferred. Consequently, the scientific community focused on energy solutions is actively searching for material sources that can facilitate cost-effective manufacturing of energy generation and storage devices, enhance performance metrics, and ensure prolonged operational life.

Food wastes encompass a variety of discarded edibles, including boiled, baked, or grilled grains (such as rice, wheat, pulses, seeds, and nuts), as well as fruits and vegetables. The decomposition of food waste produces harmful byproducts like ammonia, sulphides, acetic acid, benzene, and amines, all of which can be detrimental to environmental cleanliness. Proper disposal of food waste itself presents a significant challenge in metropolitan areas. For instance, a comprehensive study conducted by Innovation Australia Limited (FIAL) has unveiled the staggering impact of food waste on the Australian economy, amounting to approximately \$36.6 billion annually. This equates to an astounding waste of about \$2,000 per household each year and contributes to 3% of the nation's annual

greenhouse gas emissions.[72] The notion of repurposing food waste into useful products is commendable, and the idea of converting it into power devices and linking the generated energy to power grids is truly inspiring. Food waste materials are notably versatile, abundant, and cost-effective, making them an ideal resource for obtaining carbon. The resulting carbon can exhibit various morphologies based on specific processing conditions and can be further activated, allowing it to serve as a suitable host material for metal anodes. This approach holds the potential to significantly reduce the consumption of alkali metals in batteries, aligning with the principles of the circular economy and green technologies currently sought after. Recyclability and reusability are pivotal considerations in today's world, and interestingly, there is ample potential for food waste-based carbon products to be integrated into batteries. With extensive research and publications in this domain, food waste-derived activated carbon has already found applications in various energy generation and storage devices.[73-76]

This comprehensive review covers several key aspects: a) It delves into the carbonization of raw food waste, employing a range of synthetic strategies and processing methods such as pyrolysis, solvothermal techniques, and microwave approaches. The detailed exploration in this section focuses on the creation of designer carbon-based nanostructures. b) The review also addresses the activation of these carbon structures through physico-chemical treatments using various activating agents. This process is essential for the creation and manipulation of meso- and micro-porosity within the carbon, enhancing its performance. c) Additionally, it provides examples of the fabrication of energy generation and storage devices derived from food waste. It offers a comparative analysis of the performance of these devices developed over the past few years. In summary, food waste-derived

energy storage devices offer a multitude of benefits, including zero-contaminants, reproducibility, traceability, stability, and sustainability.

Although the morphology, porosity, and electrochemically active sites within nanoporous structures can be precisely controlled through a combination of synthesis and treatment conditions, it's crucial to note that the chemical composition of the porous framework primarily originates from the contents of the initial food waste, in addition to any treatment additives and the specific conditions applied. Despite numerous review articles in this research field, there is a noticeable gap when it comes to a focused review that comprehensively covers food waste-derived carbon-based energy devices, including the synthesis conditions and the intricate relationships between structure and properties.

## **2. Exploiting waste food as a carbon source**

In recent years, significant achievements have been made in converting food waste into various carbon allotropes with diverse morphologies, and these breakthroughs have been widely documented[77]. For energy generation and storage devices, the surface area of these carbon morphologies is of paramount importance, as a higher surface area can accommodate a larger number of Li/Na ions, thus enhancing their performance[78]. Notably, recent years have seen dedicated efforts to synthesize high surface area carbon materials from food waste. For instance, coffee grounds were utilized to produce carbon with an exceptionally high surface area of 3549 m<sup>2</sup>/g, demonstrating a capacitance value of approximately 440 F/g at 0.5 A/g.<sup>4</sup> Additionally, Stock et al.[79] reported the synthesis of activated carbons with surface areas ranging from 2680 to 3300 m<sup>2</sup>/g derived from used coffee grounds and coffee silver skins through the carbonization process. In another noteworthy report, rice

husk was shown to be capable of producing activated carbon encapsulated with silicon spheres through magnesiothermic reduction.

Amount of food wastage varies from country to country, and a comparative chart is presented in **Figure 1 (a)**[80]. Thus, the disposal of food waste from various sources is a huge task for municipalities and regional governments. Regarding the applicability of these food wastes as energy storage materials, it seems worth doing, keeping in mind its easy availability at an economical cost, facile synthesis, and environmental friendliness. In contrast, commercially used energy storage materials are costly, toxic, and difficult to synthesize due to their cumbersome synthetic protocols (**Figure 1(b)**). Interestingly, the specific capacitance performance of supercapacitor devices (**Figure 1(c)**)[81-84] and specific capacity values of Li/Na ion batteries (**Figure 1(d)**)[85-87] of food waste-derived carbon have been demonstrated to be comparable and with adequate functionalization, it is even better than the existing materials systems.

Food waste-derived nanoporous carbon materials can be considered as a new class of energy storage materials with several advantages over the existing commercial energy storage materials. Apart from their economic cost, easy availability, and facile synthetic protocols, as mentioned earlier, they are chemically stable and support fast ion kinetics. Renewable natural sources with worldwide availability at no cost and importantly their non-toxic nature are salient characteristics, rendering them lucrative to be employed in energy storage applications (as summarized in **Figure 2**).

The importance of achieving a high degree of crystalline order in carbon nanostructures cannot be overstated when it comes to determining their electrical conductivity. Therefore, the direct synthesis of the remarkable wonder material, graphene, from waste carbon sources takes on a central role. In line with this

objective, a significant milestone was achieved through the conversion of rice husk into graphene at a temperature of 800 °C. Furthermore, through activation with KOH at 900 °C, graphene was effectively harnessed for supercapacitor applications. In other related efforts, carbon spheres and reduced graphene oxide (rGO) nanoflakes were successfully derived from sugarcane bagasse and coconut coir, respectively.<sup>7,8</sup> Depending on the specific synthesis conditions and precursor composition, a wide range of nanocarbons can be produced from food waste, including graphene,[88] carbon dots (CDs),[89] carbon quantum dots (CQDs),[90] carbon nano onions (CNOs),[91] graphene quantum dots (GQDs),[92] carbon nanotubes (CNTs),[93,94] porous carbon,[95,96] carbon nano mesh,[97] and carbon aerogels.[98] This diversification of carbon nanomaterials from food waste holds great promise and potential.

Previous endeavours have focused on enhancing the synthesis methods of nanocarbon-based composites for their applications in energy storage.[99] In order to fabricate nanoporous carbon materials tailored to specific applications, it is imperative to optimize crucial process parameters, including carbonization temperature, activation duration, and activating agent concentration. Food waste typically exhibits a high moisture content, which can be advantageous for certain conversion processes such as anaerobic digestion (AD), fermentation, hydrolysis, and hydrothermal carbonization (HTC). However, in some cases, size reduction or pre-treatment methods like ultrasound, microwave, or pulsed electric field may be necessary to enhance the conversion process and extract value-added products.[80] Electrochemical performances of food waste-derived carbon in batteries or supercapacitors are summarized in **Table 1**.

Varieties of food wastes have the presence of elements other than carbon such as nitrogen (meat), phosphorous (seafood/red meat/nuts/poultry), sulfur (garlic/ginger), calcium(sesame/milk/greenvegetables/nuts/seeds), magnesium(spinach/banana/avocado/almond) and iron (beetroot) etc. **Table 2** summarises the ratio of C, N, H and oxygen.[125] Co-existence of these elements along with carbon in waste food can result in porosity formation due to the gasification of these elements (e.g., N will convert to  $\text{NO}_2$ , S will convert to  $\text{SO}_2$ ). Moreover, the presence of these elements post-pyrolysis in carbon skeleton will give rise to better electrochemical behaviour as compared to carbon nanostructures without these elements. Other than the presence of these non-carbon elements, different waste food items result in different particle size/porosity/morphology, giving rise to distinct surface areas accessible for lithiation/sodiation. The subsequent sections extensively delve into the strategic development of methods for converting food waste into valuable and functional nanoporous carbons.

### **3. Strategies to convert waste food into nanoporous carbons**

The transformation of food waste into porous carbon involves a dual-stage carbonisation and activation process. Initially, waste food is subjected to heat in an oxygen-depleted environment, prompting its decomposition and conversion into carbon-rich material. Subsequently, activation procedures are employed to further enhance its porosity and properties.[126]

Throughout the carbonization and activation stages, volatile organic compounds and gases are released as by-products.[127] What remains is a solid material with distinct structural and physico-chemical characteristics porous carbon, which finds applications in various fields. Notably, it serves as an ideal electrode material in energy storage devices such as supercapacitors, owing to its advantageous of high

surface area and conductivity.[103] In essence, converting food waste into porous carbon via carbonization and activation offers an eco-friendly waste management solution while yielding a valuable material with multifaceted utility, particularly in the realm of green energy and beyond. (Figure 3).

### 3.1 Initial processing

The conversion of food waste into porous carbon involves a sequence of distinct stages. This process typically encompasses the following crucial steps:

**Collection and Sorting:** Food waste is gathered from diverse sources, including restaurants, households, and food processing facilities. Subsequently, it undergoes meticulous sorting to eliminate non-biodegradable materials, packaging, and any potential contaminants.

**Pre-treatment:** The sorted food waste undergoes pre-treatment to enhance its suitability for the carbon conversion process. This pre-treatment may encompass grinding, chopping, or blending the waste material to reduce particle size and augment its surface area.

**Drying:** The pre-treated waste food is subjected to drying procedures to eliminate excess moisture. Drying can be executed through a range of techniques, such as natural air drying and oven drying.

### 3.2 Pyrolysis or carbonisation

The pyrolysis/carbonization method, widely employed in biochar production, entails subjecting organic materials, such as food waste, to elevated temperatures ranging from 250 to 900 °C within an oxygen-deprived environment. This controlled heating process effectively breaks down the organic components within the food waste, converting them into a more stable and carbon-rich substance. Food waste is notably rich in biopolymers like cellulose, hemicellulose, and lignin.[128,129] The

pyrolysis of food waste involves the thermal degradation of these organic biopolymers across various temperature ranges. Crucial parameters, including the type of food waste, carbonization temperature, temperature ramping rate, holding time, particle size, and gas flow rate, significantly influence the properties and yield of the desired end product-biochar.[130] The composition and physicochemical attributes of biochar derived from food waste are profoundly shaped by the pyrolysis process, as it exerts a pivotal role in determining these characteristics. For instance, Kane and Ryan conducted pyrolysis on post-consumer food waste, converting it into biochar at a high temperature of 900 °C (**Figure 4a**)[131]. This resulting biochar exhibits properties comparable to carbon black and holds potential as a filler in the production of biodegradable plastics. Moreover, biochar can serve as a precursor for the creation of porous carbon, which finds utility in diverse applications, including gas capture and energy storage. Additionally, the carbonization of waste food is vital in mitigating greenhouse gas emissions. By diverting organic food waste away from landfills, where it would otherwise decompose and emit methane (a potent greenhouse gas), the carbonization process helps reduce the environmental footprint of food waste into value-added products. Carbonization is a cost-effective strategy to manage the overall expenditure of the production of food waste-derived porous carbons. As an estimate, for one kg of porous carbon production, 3.295 kWh of energy is required, which equates to a commercial price of \$1.34 for one kg[132-134]. These numbers are reasonable when compared to some of the other materials which are synthesised from various expensive chemicals as starting precursors. In summary, the carbonization of food waste represents an effective and environmentally friendly solution for managing organic waste while simultaneously generating a valuable resource in the form of biochar.[135]

### 3.3 Activation

From an application perspective, achieving high performance hinges on the crucial step of converting food waste biochar into porous carbons through the activation process. Activation entails subjecting food waste to elevated temperatures in the presence of an activating agent, which may include steam, CO<sub>2</sub>, or chemical compounds like potassium hydroxide (KOH) and zinc chloride (ZnCl<sub>2</sub>).<sup>[116,139]</sup> This thermal treatment effectively dismantles the intricate organic compounds within the food waste, resulting in the formation of porous carbon. During activation, volatile components are driven off, leaving behind a carbonaceous residue. The choice of activating agent and the activation conditions, including temperature and duration, can be fine-tuned to achieve specific properties in the resulting porous carbon. The activating agent plays a pivotal role in creating an interconnected network of pores within the carbon structure, thereby enhancing its porosity. The substantial surface area and porosity rendered by this process make porous carbon an exceptional material for diverse applications, such as water and air purification, pollutant removal, and gas storage. Additionally, it finds utility as catalyst support, serves as an electrode material in energy storage devices (e.g., supercapacitors), or functions as a reinforcing component in composite materials.

#### 3.3.1 Chemical Activation

Chemical activation is a process that entails the treatment of food waste materials with a specific chemical agent (acid or alkali), commonly an activating agent like H<sub>2</sub>SO<sub>4</sub>, phosphoric acid (H<sub>3</sub>PO<sub>4</sub>), KOH, or zinc chloride (ZnCl<sub>2</sub>), followed by a high-temperature carbonization step. In the initial stage of chemical activation, food waste material is impregnated with the activating agent. This is typically achieved by

immersing the food waste in a solution containing the activating agent. The activating agent initiates a series of chemical reactions with the carbonaceous constituents within the food waste. After impregnation, the activated food waste is exposed to high temperatures, typically within the range of 500 to 900 °C, in an inert atmosphere, often using nitrogen. During carbonization, the activating agent catalyses reactions with the carbon precursors in the food waste, facilitating the release of volatile components and fostering the creation of pores within the carbon structure. The activating agent also plays a pivotal role in enhancing the formation of a porous network, leading to an increase in the surface area of the resultant carbon material. The resulting porous carbon material, achieved through chemical activation, exhibits remarkable features, including a substantial surface area and a well-defined pore structure.[140] These characteristics render it highly suitable for an array of applications, spanning adsorption, water treatment, energy storage, and catalytic processes.

Wu et al. conducted a notable study wherein fish skin served as the precursor for synthesizing porous carbon through KOH-based chemical activation. The resultant porous carbon was subsequently hybridized with NiCo/CoNiO<sub>2</sub> for its application in electromagnetic wave absorption.[136] The synthesis process, illustrated in **Figure 4b**, involved several key steps, encompassing wet impregnation, freeze drying, hydrothermal carbonization, and subsequent carbonization cum activation at elevated temperatures. In another insightful investigation by Adebayo et al., porous carbon was derived from banana peels and then integrated into a composite with CO<sub>3</sub>O<sub>4</sub> for microwave absorption applications.[137] As depicted in **Figure 4c**, the researchers employed a wet impregnation technique, mixing KOH with banana peel powder, followed by carbonization at temperatures of 500, 600, and 700 °C. This

resulted in the development of porous carbons with a combined micro/meso structure. Santosh and Dawn demonstrated the activation of food waste with zinc chloride and the proposed method could yield stable porous carbons enriched in mesopores.[138] They utilized four different types of sun-dried food waste in their study, including rice, vegetables, oil, and spice (WCVR); mixed fruit peels such as banana peel, pomegranate peel, orange peel, and lemon peel (MFPW); plain rice (WCR); and mixed food waste comprising rice, dhal, vegetables, fruits, meat, and bones (MFW). These food waste samples underwent activation with zinc chloride at temperatures ranging from 500 to 600 °C for a duration of 2 h, as shown in **Figure 4d**. The prepared materials were found to be excellent adsorbents for efficiently treating biodiesel wash water. In summary, chemical activation proves to be an effective method for transforming waste food into porous carbon. By employing activating agents and high-temperature carbonization, this process converts organic waste into a valuable resource, exhibiting desirable properties for various applications. Moreover, the resulting porous carbon has the potential to serve as a sustainable substitute for activated carbon derived from non-renewable sources across a spectrum of industrial applications.

### 3.3.2 Physical Activation

Physical activation presents another avenue for creating porous carbon from food waste. In contrast to chemical activation, which relies on activating agents, physical activation harnesses-controlled heat alongside physical agents like steam or carbon dioxide to instigate pore formation and the development of the carbon material's porous structure. The physical activation process typically unfolds in two primary steps: carbonization and activation. During carbonization, the food waste material is exposed to high temperatures, typically within the range of 600 to 900 °C, under an

inert atmosphere. This thermal treatment initiates the pyrolysis of the organic constituents within the food waste, ultimately yielding a carbonaceous residue. Following carbonization, the carbonaceous residue undergoes an activation phase, which entails additional heating in the presence of an oxidizing agent, such as steam or carbon dioxide. The oxidizing agent engages with the carbonaceous material, inducing gasification. This gasification process generates voids and pores within the carbon structure, fostering the development of a porous network. The effectiveness of the physical activation process hinges on several key factors, including temperature, duration, and the nature of the oxidizing agent employed. These parameters can be optimized to control the pore size distribution, surface area, and overall porosity of the resultant carbon material precisely. The porous carbons produced by physical activation possess high surface areas and well-defined pore structures and are promising for many applications. Its versatility extends to applications in adsorption, gas separation, energy storage, and catalytic processes.

Valla et al. conducted a comprehensive study to probe the influence of experimental conditions on the transformation of waste food into porous carbon via a two-step steam-based physical activation process, as depicted in **Figure 5a**.<sup>[141]</sup> Initially, the waste food underwent pyrolysis, spanning temperatures from 275 to 525 °C, resulting in varying yields of biochar. Intriguingly, the highest biochar yield was obtained at 275 °C, while the lowest yield was achieved at 525 °C. The biochar produced at 525 °C then underwent a subsequent steam activation step, carried out within a temperature range of 750-950 °C. Notably, a higher yield of activated carbon was attained at lower temperatures during this activation step. High temperature pyrolysis however yields carbon burn off. Remarkably, the highest surface area, measuring 745 m<sup>2</sup>/g, was reached when activation was executed at 950 °C with a

residence time of 1 hour. Conversely, residence times of 3 and 4 h resulted in reduced surface areas of 684 and 550 m<sup>2</sup>/g, respectively. Microscopic analysis of the biochar revealed a non-porous morphology, while the porous carbon acquired through the physical activation at 950 °C exhibited distinct porous structures, as illustrated in **Figures 5b and c**. In a separate investigation, Taer et al. explored the activation of bread waste utilizing CO<sub>2</sub>. Their findings underscored the capacity of physical activation to engender the formation of a hierarchical porous structure in carbon, encompassing micro, meso, and macro pores.[115] The experimental procedure entailed initially by exposing bread waste to a N<sub>2</sub> atmosphere at 600 °C, followed by switching to CO<sub>2</sub> at elevated temperatures of 800 °C, 850 °C, and 900 °C, as portrayed in **Figure 5d**. The utilization of CO<sub>2</sub> as the activation agent indeed gave rise to the development of hierarchical porous structures within the carbon material.

Physical activation represents a relatively straightforward and cost-effective approach that can be implemented with standard equipment. Nevertheless, it results in carbon materials with a lower degree of porosity compared to those achieved through chemical activation. To sum up, physical activation is a method that leverages heat and an oxidizing agent to generate a porous carbon structure from food waste. This method presents an eco-friendly means of converting organic food waste into a valuable material with diverse potential applications.

### **3.4 Hydrothermal Carbonisation**

Hydrothermal carbonization (HTC) is a transformative process that converts organic materials, like food waste, into carbon-based materials by harnessing a combination of heat, pressure, and water.[143] In the HTC procedure, waste food is initially blended with water to form a slurry. This slurry is then subjected to elevated

temperatures (typically in the range of 180-250 °C) and high pressures (up to 25 bar) within a sealed reactor. Under these conditions, the organic compounds within the slurry undergo a series of intricate chemical reactions, including hydrolysis, dehydration, and polymerization, which dismantle the complex organic molecules and reconstruct them into carbon-rich solids referred to as hydrochars. Subsequently, these hydrochars are often further activated to yield porous carbon materials. Notably, the carbonization process can be adjusted and fine-tuned to precisely control the properties of the resulting hydrochars, encompassing their porosity, surface chemistry, and thermal stability. By modifying key process parameters, such as temperature, reaction time, and the composition of the feedstock, it becomes feasible to tailor the characteristics of the porous carbons to meet specific application requirements.

Hydrochars derived from food waste exhibit promising attributes as energy fuels, primarily due to their high carbon content and substantial heating value. In a notable study by Yan et al., they proposed that food waste subjected to oil extraction served as an exceptional precursor for producing energy-rich hydrochar, featuring a high heating value within the range of 21.13 to 24.07 MJ/kg and an elevated fuel ratio ranging from 0.112 to 0.146.[142] The authors employed hydrothermal carbonization (HTC) in an aqueous environment within a batch reactor, using a combination of three different temperatures and varying residence times to yield carbon-rich hydrochar, as depicted in **Figures 5e-h**. Similarly, in the work of Xing et al., HTC was applied to generate a substantial volume of hydrochar from two distinct types of food waste: leftover steamed bread and pitaya peel.[144] In their study, a pilot-scale hydrothermal reactor was used to produce hydrochar from 1 kg of food waste, operating at 260 °C for a duration of 3 h. It's important to note that in these

examples, the primary application of hydrochar was for the removal of various ions from the solution. However, the current literature lacks comprehensive studies examining the utilization of food waste-derived hydrochar for energy storage purposes. Consequently, there exists a clear need for further research and exploration in this domain. The structure of the final carbon product formed via the utilization of the above-discussed synthesis processes depends on the starting food waste resource, however, in general, the carbon in the precursor becomes concentrated upon thermal heating and forms an aromatic network. The possible structure of the formed porous carbon has been predicted to be accompanied by several types of functional groups as shown in **Figure 6**.

In summary, activation, encompassing both physical and chemical methods, offers a practical and efficient avenue to produce porous carbon from diverse organic carbonaceous sources, such as food waste. Continual progress in synthesis techniques allows for the creation of increasingly sophisticated materials using food waste as a foundational component. These materials can feature elevated surface areas, substantial pore volumes, finely tuned porosity, and appropriate surface functionalization, ultimately resulting in enhanced performance across a broad spectrum of applications.

#### **4. Characterization techniques**

The characterization of food waste-derived nanoporous carbon, with a particular emphasis on functionalization, graphitization, and textural parameters, is crucial for tailoring their properties and potential in energy applications. Several characterisation techniques including scanning electron microscopy (SEM), transmission electron microscopy (TEM), powder X-ray diffraction, Raman, FT-IR, and XPS spectroscopies, N<sub>2</sub> adsorption and thermogravimetric analysis, have been employed to evaluate the surface

and morphology, crystallinity, chemical structure, stability and the functional groups of the food waste-derived nanoporous carbons, and some of these will be discussed here.

#### 4.1 SEM and TEM

SEM and TEM are invaluable tools for visualizing the morphology and pore structure at various length scales, providing essential insights into the presence of interconnected pores, and allowing estimation of pore sizes. SEM and TEM imaging also facilitate the assessment of the carbonization and activation degree of porous carbon derived from food waste. A comparison of images between the initial material (coffee ground) and the resulting carbon can reveal structural alterations, pore formation, and the removal of impurities during the carbonization and activation processes (**Figure 7a-b**). Similarly, after carbonization at 700 °C, waste coffee grounds transform into a honeycomb-like structure with numerous large cavities measuring approximately 50 µm, and this structure is preserved after following activation (**Figure 7c**).<sup>[124]</sup> In another report, Hou et al. reported on the tunable porous structure of carbon nanosheets derived from puffed rice, as illustrated in **Figure 7d**.<sup>[104]</sup> The laminar and porous structure of the nanosheets is conducive to the faster diffusion of electrolyte ions for improved supercapacitor performance.

#### 4.2 Nitrogen adsorption/desorption isotherms

Textural parameters play a pivotal role in evaluating the physical attributes of porous carbon derived from food waste, encompassing aspects like surface area, porosity, and pore size distribution. These parameters will significantly influence the performance of the materials in energy storage. Nitrogen adsorption/desorption isotherms serve as invaluable tools for extracting data related to pore volume, pore size distribution, and specific surface area (SSA), thus enabling the quantification of the porosity of the materials. For example, BET specific surface area for KOH-

activated carbon derived from waste potato peel, calculated from adsorption/desorption isotherms is measured to be 1911.5, 1645.8, and 1493.3 m<sup>2</sup>/g for P/PAC (phosphorus doped porous activated carbon), S/PAC (sulfur doped porous activated carbon), and PAC (porous activated carbon), respectively (as indicated in **Figure 7e**).<sup>[105]</sup> Furthermore, the Density Functional Theory (DFT) calculation of pore size distribution reveals that the pore size falls within the range of <2 nm, with corresponding pore volumes of 1.17, 0.78, and 0.67 cm<sup>3</sup>/g, respectively (as shown in **Figure 7f**)<sup>[105]</sup>. The substantial SSA, presence of microporosity, and significant pore volume collectively contribute to the enhancement of the electrochemical storage behaviour of the potato peel-derived nanoporous carbon.

#### **4.3 Fourier-transform infrared spectroscopy (FTIR)**

Functionalization plays a pivotal role in augmenting the surface chemistry and attributes of porous carbon materials originating from food waste. An array of techniques, including chemical treatment, physical adsorption, and covalent attachment, facilitates the incorporation of specific functional groups or modifications. It's worth noting that the reversible redox processes involving oxygen and nitrogen-containing groups with charge can trigger additional faradaic reactions. A crucial aspect of this process involves characterizing the functionalization to evaluate the efficiency and stability of the introduced functional groups. FTIR represents a powerful tool in this context, relying on the interaction of substances with infrared light through absorption, transmission, or reflection. It furnishes essential insights into the nature and types of functional groups by analyzing characteristic vibrational frequencies, thereby enabling an assessment of the synthesis and structural integrity of the target products. For example, FTIR spectral analysis of porous carbon derived from citrus peel fiber waste reveals the presence of distinct functional groups,

including C=C, -O-H, and C=O, as indicated by 1581, 3430, and 1793  $\text{cm}^{-1}$  bands, respectively (as illustrated in **Figure 7g**). These functional groups help in better lithiation/sodiation and thus can have a beneficial impact on charge storage, ultimately resulting in an increased capacitance for carbon-based materials[109],[145].

#### 4.4 X-ray diffraction (XRD)

XRD analysis provides a means to detect graphitic planes and assess the level of crystallinity in materials. In a typical XRD spectrum of carbon derived from food waste, one observes a broad peak at approximately  $22^\circ$ , corresponding to the (002) reflection of the graphitic stacking, and a weaker peak around  $43^\circ$ , associated with the (101) reflections (as depicted in **Figure 7h**).[115,117,146-148] The broad nature of these peaks signifies the presence of porous carbon with low crystallinity, indicating that the original material has undergone efficient conversion into amorphous carbon. In general, an adequate level of crystallinity and porosity, as well as electrochemically active sites, are desirable for enhanced device performance. Moreover, the distinct increases in the low-angle region can be attributed to the formation of numerous nanopores.

#### 4.5 Raman spectroscopy

Graphitization represents a transformative process that enhances the structural order and properties of porous carbon materials. In the specific context of porous carbon derived from food waste, graphitization involves the reconfiguration of carbon atoms to establish  $\text{sp}^2$  hybridized carbon bonds, which, in turn, results in improved electrical conductivity and mechanical strength. A comprehensive understanding and characterization of the degree of graphitization are paramount for optimizing the material's performance in particular applications. Raman spectroscopy stands as a

pivotal tool for obtaining valuable insights into the structural order and the presence of graphitic domains, all based on the distinctive Raman peaks. Notably, the D-band ( $\sim 1360\text{ cm}^{-1}$ ) emanates from the in-plane distortion of the graphene sheets and may be linked to the  $\text{sp}^3$  hybridization of carbon atoms. The G-band ( $\sim 1560\text{ cm}^{-1}$ ), on the other hand, is rooted in the in-plane stretching of the  $\text{sp}^2$ -bonds within the aromatic carbon rings (as illustrated in **Figure 7i**). Additionally, the 2D band ( $\sim 2870\text{ cm}^{-1}$ ), situated at approximately twice the frequency of the D-band, is a product of second order scattering processes. A broad and featureless 2D band serves as a characteristic trait of turbostratic carbons.[79]

The intensity ratio of the D-band and G-band ( $I_D/I_G$ ) serves as a valuable metric for gauging the extent of graphitic ordering within a material. Smaller  $I_D/I_G$  values in the prepared samples correspond to higher degrees of graphitization, reflecting a more regular and orderly structural arrangement. For instance, as the activation temperature of carbon nanosheets derived from puffed rice increased, the  $I_G/I_D$  value rose from 0.78 to 0.95, potentially attributed to the elevated activation temperature's interaction with the more graphitized areas within the carbon particles.[104] In the case of sheet-like porous carbon (SPC) resulting from the carbonization of eggplant, the defect concentration increases with rise in carbonization temperatures, ranging from 700 to 1000 °C due to the increased exposure of edges during the pore evolution process giving rise to enhanced defect formation.[149] In fact, defect generation is preferred over crystallization, if elements other than carbon are present in biomass precursor. Additionally, an increase in the annealing temperature for N, O-enriched corn silk-derived carbon leads to a decrease in the degree of graphitization.[150]

#### 4.6 X-ray photoelectron spectroscopy (XPS)

X-ray Photoelectron Spectroscopy (XPS) is a surface characterization instrument which is capable of revealing binding energy for all chemical bonds present at surface of the material and thus can serve as a valuable tool for ascertaining the surface elemental composition and oxidation states of functional groups, thus contributing to a comprehensive understanding of surface chemistry alterations. Through elemental analysis, it provides crucial insights about purity/quality of materials under consideration. It helps quantify elemental composition, oxidation states, elemental doping, surface functionalities etc. For example, in the XPS C 1s spectra of nano porous carbon derived from waste bean-curd dregs, the C 1s peaks reveal the presence of C=C, C-C, C-O, and O-C=O bonds, with calculated O/C ratios yielding similar values of 0.05 and 0.06, respectively (as illustrated in **Figure 7j**). From the XPS results, it was also concluded that the type of activation and the amount of activation are the keys to controlling the surface functional groups. For example, the oxygen functional groups on the surface of the porous carbon can be reduced with the concomitant increase of the defective carbon building blocks and larger ultramicropores through a harsher activation process. Intriguingly, despite their comparable heteroatom content, a notable distinction in pseudo capacitance is evident in the voltage-dependent cyclic voltammetry (CV) curves, due primarily to surface chemistry.[147]

#### **4.7 Thermogravimetric Analysis (TGA)**

TGA is a technique to study the weight loss of materials with elevated temperatures in order to understand the stability of functional groups and the phase change of materials, which is very useful for analyzing the pyrolysis of food waste (often carried out in nitrogen).[151] TGA analysis can identify the specific temperature points and ranges corresponding to the devolatilization of food waste, offering both qualitative

and quantitative insights into the organic composition of the sample.[152] For example, from the TGA curves, the initial reduction in weight observed at a relatively low temperature can be attributed to sample dehydration. Weight loss at higher temperatures is complicated. It could be the phase change or reaction of the materials or the decomposition of the surface functional groups. For example, for the analysis of areca nut husk based biomass using TGA, the weight loss occurring between 150-350 °C, between 265 and 350 °C and at 450 °C is due to the combustion of hemicellulose, cellulose, and lignin, respectively.[148] It's noteworthy that the TGA profile from this study closely aligns with the decomposition behaviour of different lignocellulosic fibres documented in prior research, such as banana, sugarcane bagasse, Acacia mangium, and Acacia hybrid wood species.[153,154]

## **5. Energy storage applications of food waste derived porous carbons**

### **5.1 Food waste derived activated carbon for supercapacitors**

Supercapacitors represent a class of next-generation energy storage devices that have gained increasing popularity due to their remarkable attributes, including high power density, exceptional cyclability, and robust stability[155]. Supercapacitors principally rely on either the electrochemical double-layer capacitance (EDLC) or the pseudo capacitance mechanism, with each approach offering its own set of advantages and drawbacks[9]. The specific properties of these mechanisms can be tailored based on the requirements of the supercapacitor device. For instance, given that EDLC operates by physically adsorbing ions on the surface of the electrode material, porous carbons emerge as one of the most highly sought-after materials for EDLC-based supercapacitors owing to their high specific surface area and their cost effectiveness.[156]

Qiao et al. demonstrated the role of various food waste components such as starch, protein, and lignocellulose on their specific capacitance. While the material derived from starch rich carbon source delivered a higher retention rate in supercapacitor device, protein and lignocellulose based carbon exhibited higher capacitance (327 F/g at 0.5 A/g) than other porous carbon materials[157] (**Figure 8a**). Furthermore, research in the realm of food waste-derived supercapacitor materials has explored alternative activation methods. For instance, bread waste was subjected to physical activation, resulting in an impressive surface area of 610.5 m<sup>2</sup>/g and a specific capacitance of 202 F/g at 1 A/g when tested with a 1M H<sub>2</sub>SO<sub>4</sub> electrolyte in a coin cell setup. This led to an impressive energy density of 11.61 Wh/kg at a power density of 156.71 Wh/kg measured in a coin cell setup.[158] Similarly, idly, a common Indian food item primarily composed of protein and starch, was activated using KOH, achieving a capacitance of 280 F/g at a current density of 1 A/g, with a capacitance retention of 96.1 % after 10,000 cycles.[159] While the role of surface area and porosity is well recognised in the literature, the functional groups present on the carbon surface enable certain redox reactions which may play a significant role in enhancing storage capabilities of the supercapacitor assembly. Therefore, the study amplifies the need for understanding the functional groups on the surface of the carbon derived from the food waste precursors as it directly affects the super capacitive performance.

In an intriguing example, rotten potato waste, which may contain alkali metals like sodium and potassium, presented a unique self-catalytic activation strategy. This method led to a surface area of 2201 m<sup>2</sup>/g and a capacitance of 220 F/g at 0.5 A/g g<sup>1</sup>, contributing to a more sustainable process by eliminating the need for external activating agents.[117] Cooked chicken bone food waste, a major source of waste,

especially in countries where it is utilized as dog food, was subjected to KOH activation, yielding a capacitance of 218 F/g at 0.5 A/g in 3M KOH with a potential window of 1.05 V.[114] In a novel approach, the process of transpiration facilitated the transfer of erioglaucline disodium salt to the salt of cabbage leaves, which led to self-activation. This method resulted in a surface area of 778 m<sup>2</sup>/g and a capacitance of 171.6 F/g at a scan rate of 2 mV/s, thereby making the process more eco-friendly. [108] Food waste generated in university dining halls worldwide was harnessed to produce edge defect-rich porous carbon, resulting in a specific capacitance of 442 F/g at 0.5 A/g. The measurements were carried out in 6 M KOH acting as the electrolyte, and the prepared material also showed a 94.4 % capacitance retention after 10,000 cycles, demonstrating its electrochemical stability.[160] In another report, Peng et al. employed ZnCl<sub>2</sub> and KOH to synthesize activated carbon from mango stones, a rich source of fat. This approach yielded a capacitance 229 F/g at higher current densities of 50 A/g with an energy density of 27.6 Wh/kg at a power density of 159.9 Wh/kg. [113] Another study involved carbonization of alkali-treated flour in a one-step process with heteroatom doping, yielding a specific surface area of 1313 m<sup>2</sup>/g, resulting in an outstanding capacitance of 473 F/g at 0.5 A/g. This device exhibited a wide operating voltage window of 2V, demonstrating the significant potential of these activated carbons with heteroatom doping<sup>[119]</sup> (**Figure 8b**). Supercapacitance (symmetrical) performance of flour-derived porous carbon as compared to other materials was revealed by Ragone plot. (**Figure 8c**) Furthermore, activated flour food showed impressive capacitance retention, exceeding 50%, even at a high current density of 100 A/g, underscoring the robust nature of carbon electrodes.[122]

The utilization of nanoporous carbon derived from abundant food waste, including the examples mentioned and various others, holds significant promise for applications as supercapacitor electrodes. The unique porosity, coupled with its high surface area and other beneficial attributes of these nanoporous carbons, make them as compelling candidates for energy storage applications. The cost-effectiveness of these precursors, along with the prospect of addressing waste management challenges, renders this approach exceptionally sustainable. The considerable surface area and tunable porosity of food waste-derived activated carbon are directly influenced by the activation parameters. These parameters, encompassing factors like temperature, amount, and the choice of activating agent, provide a versatile framework for optimization. When thoughtfully adjusted in conjunction with the diverse biomass feedstock available, these parameters enable the attainment of highly desirable material properties at a minimal cost[161,162]. The unique porosity and the nanochannels enable efficient ion diffusion. Further, the high surface area is well known to directly play a role in the capacitance of the material. Most importantly, porous carbon-based electrodes are conductive and robust which lead to increased electrochemical stability and cycling. These properties can further be enhanced by effective strategies such as heteroatom doping, tuning the porosity, and modulating the surface functional groups. Due to these characteristics, food waste derived nanoporous carbon is one of the most sought-after materials to be used as supercapacitor electrodes. Thus, food waste-derived nanoporous carbon presents a green and economically viable solution to the clean energy storage challenge.

## **5.2 Food waste derived activated carbon for batteries**

Leveraging waste food products like fruit peels, coffee grounds, and rice husks as raw materials in the creation of nanoporous carbon offers a captivating avenue for repurposing organic waste. These waste food products inherently feature a 3D carbon skeleton. Consequently, the carbonization process applied to them yields a substantial increase in micro and nanopores, a feature that significantly augments ion diffusion, enhances electrolyte accessibility, amplifies surface area, and ultimately elevates battery performance.[110,111,163,164] [165-167] Carbon nanofibers is another material that displays favourable characteristics towards battery applications. Walnut shell derived carbon nanofibers through the process of liquefaction, electrospinning, and carbonization displayed excellent cycling performance, with a high degree of reversibility (achieving over 280 mAh/g specific capacity after 200 cycles at 0.1 A/g in lithium-ion batteries (**Figure 9(a)**) [168] Serna-Jiménez and colleagues,[169] for instance, designed an activated carbon named BPW-C, derived from the calcination of banana peel waste with the inclusion of KOH in the activation process (**Figure 9 (b)**). It exhibited a porous structure, as observed in SEM images (**Figures 9 (c, e, f)**) This treatment increased the surface area of BPW-C to 264 m<sup>2</sup>/g which led to a reversible capacity of 225 mAh/g at 0.2 C after 200 cycles in lithium-ion batteries. Similarly, the effects of different porogens (H<sub>3</sub>PO<sub>4</sub>, KOH, and ZnCl<sub>2</sub>) in the development of disordered carbons from banana peel waste (BPW) have been extensively studied. The material showed a capacity fade in the first few cycles, however, maintained a stable reversible capacity of 272 mAh/g at 0.2 C after 200 cycles with minimal resistance of 114 Ω (**Figure 9 (d)**).

Further, Raj et al. [170] reported the synthesis of nanoporous carbons from the seeds of Litchi chinensis, which displayed its utility in sodium ion batteries wherein due to the presence disorder and defect sites. The optimized biocarbon delivered an

electrochemical reversible specific capacity of approximately 146 mAh/g at a current density of 0.2 A/g after 100 cycles. In the full cell prototype, the litchi derived nanoporous carbon showed the specific capacity of 266 mAh/g at 0.1 A/g and the full cell is stable even for more 50 cycles, demonstrating its robustness, stability and performance.

Cuttlebone subjected to activation results in heteroatom doping with N and O with a hierarchical porous structure, which assists in increased sodium cycling stability.**[171]** enhances doping is another effective strategy to improve the energy density of sodium-ion batteries. For instance, amorphous carbon doped with N, O, S was synthesized from cassava peel For instance, a porous carbon/MoS<sub>2</sub> composite derived from rice husks exhibits favourable interface kinetics, higher conductivity resulting in a coulombic efficiency of nearly 100% even after the 60<sup>th</sup> charge/discharge cycles.**[123]**

The heteroatom doping combined with metal oxide functionalisation on the surface of the nanoporous carbons derived from food waste products is another effective strategy to improve the electronic conductivity and the performance of the food derived nanoporous carbon based electrodes. A noteworthy example is the synthesis of a nitrogen-doped 3D porous starch-derived carbon/SnO<sub>2</sub>/carbon (PSC/SnO<sub>2</sub>/C) composite.**[172]** Nitrogen doping in this composite is facilitated by the N-containing protein in starch. The introduction of nitrogen atoms increases the number of defects and active sites available for Li/Na storage, while Sn–O–C bonds effectively reduce SnO<sub>2</sub> agglomeration. Consequently, PSC/SnO<sub>2</sub>/C exhibits efficient electron transport, achieving a specific capacity of 700 mAh/g after 100 cycles at a current density of 0.2 A/g in lithium-ion batteries. More recently, the development of single-atom catalysts based on nanoporous carbons derived from food waste products

showed promising characteristics to be used as anodes in metal ion batteries. Specifically, waste food products with higher nitrogen content provide a suitable coordination environment whereas the nanoporous structure of carbon offers numerous attachment sites for single atoms. As an example, N-doped nanoporous carbon derived from corn silk has been successfully employed as a support for Fe single atoms. This configuration resulted in a high peak power density of 101 mW cm<sup>-2</sup> and a stable discharge–charge voltage gap of 0.73 V over more than 44 h when integrated into flexible Zn–air batteries.[173]

While nanoporous carbon displays significant conductivity along with ample surface area which enables efficient ion diffusion, the doping strategies mentioned above, these are shown to enhance the power density of the electrode. Therefore, the use of activated carbon is being further explored to be used in metal ion/metal-air batteries due to its green and eco-friendly nature, tunable surface, and porosity. The surface functional groups play a significant role in enhancing the specific capacity of the material by tuning the electrochemically active redox sites, whereas the porosity helps in efficient ion diffusion of the electrolyte. The tuning of the porosity can be attributed to different synthesis factors therefore the pores may be shaped to suit the metal ion. Therefore, the food waste derived nanoporous carbon is a sought-after material to be used in next generation secondary batteries making it a green and eco-friendly alternative to currently available electrodes.

In general, binders serve a crucial role in effectively securing active material particles to the conductive agent, ensuring the stability and cycle life of electrodes. However, commonly used binders such as polyvinylidene fluoride have notable drawbacks, being expensive, toxic, and non-aqueous, which inevitably restricts their broader applications. Given the advantages of affordability and environmental friendliness, it

is highly desirable to employ cellulose derivatives as binders, particularly when sourced directly from waste food products. For example, corncobs can serve as the raw materials for both carbon production and the creation of a sodium carboxymethylcellulose binder.[174] The resulting carbon material demonstrates appropriate interlayer spacing and a favourable surface area, enabling partial bulk insertion and interfacial adsorption of sodium ions. Moreover, the strong adhesion between the carbon and sodium carboxymethylcellulose binder leads to outstanding electrochemical performance, yielding a specific capacity of 264 mAh/g at 1 C with promising capacity retention and excellent rate capability.

## 6. Summary and outlook

Food waste generated by households, restaurants, and takeaways, including items like cooked rice, pizza, vegetables, and various recipes, is typically disposed of, placing a significant burden on municipalities and government bodies. Efficient disposal requires substantial funds and resources. Transforming food waste into products that can be used in practical applications, such as powering households, has long been a dream. Practical methodologies for converting food waste into high-surface-area nanoporous carbon, along with activation protocols, hold immense promise for use in applications such as supercapacitors and batteries. This article provided a comprehensive review of recent developments in this research area, **Figure 10** summarizing the content.

Various pyrolysis methods, including high-temperature furnaces, intense lasers, Ar or N<sub>2</sub> plasma, and microwaves, were detailed as effective means of transforming food waste into micro/nano-porous carbon morphologies. Key parameters affecting the product quality include carbon sources, carbonization temperature, ramp rate, quenching rate, heating source (furnace/microwave), and heating environment (Ar,

air, N<sub>2</sub>, etc.). The article discussed the use of a range of microscopic (FESEM, AFM, TEM/HRTEM) and spectroscopic (UV-Vis, PL, Raman, XPS, XAS) tools for characterizing the physical and chemical properties of synthesized micro/nanoporous carbon morphologies. The elaborative discussion on various techniques such as nitrogen adsorption, HRTEM, and powder XRD employed for understanding the structural and pore structural features of food waste derived nanoporous carbons has been presented. Chemical stability, particularly in acidic or basic media, is crucial for the implementation of strong electrolytes, and such explorations under treatment with KOH, HCl, and H<sub>2</sub>SO<sub>4</sub> have been conducted. The present review article also elaborated on approaches to achieve in-situ/ex-situ physical/chemical activation (e.g., KOH, MgCl<sub>2</sub>, KF, MnCl<sub>2</sub>, etc.) of synthesized nanoporous carbon, showcasing how synthesis conditions influence the specific surface area, the surface functional groups, the average pore size and the pore size distribution. Various waste food resources contain different elements other than carbon, which upon pyrolysis form gaseous compounds giving rise to high surface area porous structures and simultaneously those elements are incorporated in carbon lattice which results in improved conductivity and enhanced electrochemical performances.

The utilization of activated nanocarbon in various classes of energy storage devices, including high-energy-density batteries like lithium and sodium-ion batteries, high-power-density storage devices like high-energy and power-density pseudo-capacitors (hybrids) was described in detail. Electrochemical performances, cyclability, and load and rate capabilities were compared, with most of the literature focusing on thermal (furnace) activation. The article also covered mixed activation

methods (e.g., KOH+MgCl<sub>2</sub>, ZnCl<sub>2</sub>+KF, MnCl<sub>2</sub>+KF), which can result in distinct pore sizes and distributions, eventually leading to hierarchical structures.

Considering the remarkable progress in this field of research and development, the following directions outline the prospects for future investigations (as depicted in **Figure 10**): Innovative approaches and methods should be devised to streamline processing. For example, the use of chemical treatments before or during carbonization can lower pyrolysis temperatures, enhancing efficiency. Controlled synthesis methods must be explored to yield high surface areas with well-defined pores, and employing multiple chemical agents for activation concurrently may lead to hierarchically nano-/micro-porous carbon structures. It is also crucial to ascertain the variety and geographic location of the food waste source as it could influence the physico-chemical properties of the resulting porous carbons. This is because the food-bearing plants may be inherently rich in some particular minerals that are found in a specific soil type. More research will bring out more possibilities in this regard as well. A systematic study is essential to optimize this approach for efficient energy storage. The utilization of high-energy density laser and microwave plasma for post-growth treatment can significantly enhance the crystallinity of nanocarbon, improving both the efficiency and cyclic stability of energy storage devices. Further exploration into laser and microwave plasma activation methods is warranted.

Emerging energy generation and storage devices, such as lithium-sulfur batteries, Zn-air systems, and iron-ion batteries, require extensive optimization before practical commercialization. Research efforts should be dedicated to refining these technologies. Innovations in the development of suitable liquid and solid electrolytes compatible with nanoporous carbon can greatly enhance device performance. The electrolyte should effectively activate the functional material without dissolving it.

Scalable processing technologies need to be developed for the efficient and large-scale conversion of tons of food waste into functional carbon forms. The utilization of artificial intelligence (AI) and machine learning (ML) for programmable porosity and activation can aid in experimental design. This avenue holds great promise and should be explored further.

Given the increasing public interest in using food waste to power household electric devices and eventually entire power grids, focused research endeavors are vital to bring about carbon-based future-generation energy storage devices. It's particularly significant due to its economic viability. Carbon-based energy storage technologies have the potential to make substantial progress, but there is still a considerable gap to bridge before they can match the performance of existing high-performance metal oxide-based energy storage devices. Research and development efforts must persist in this direction.

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### **Author contributions**

JMD – Preparation and revision, CIS, MRB, ZL, XZ, RB, KR – Preparation, GS – Preparation, reviewing and editing, JY – Reviewing and editing, PK - Preparation, reviewing, and editing, AV - Supervision, correction, and revision, reviewing and editing.

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We declare that none of the authors have any competing financial or non-financial interests.

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## Tables and Figures

**Table 1.** Electrochemical performances (battery/supercapacitor) of functionalized waste food.

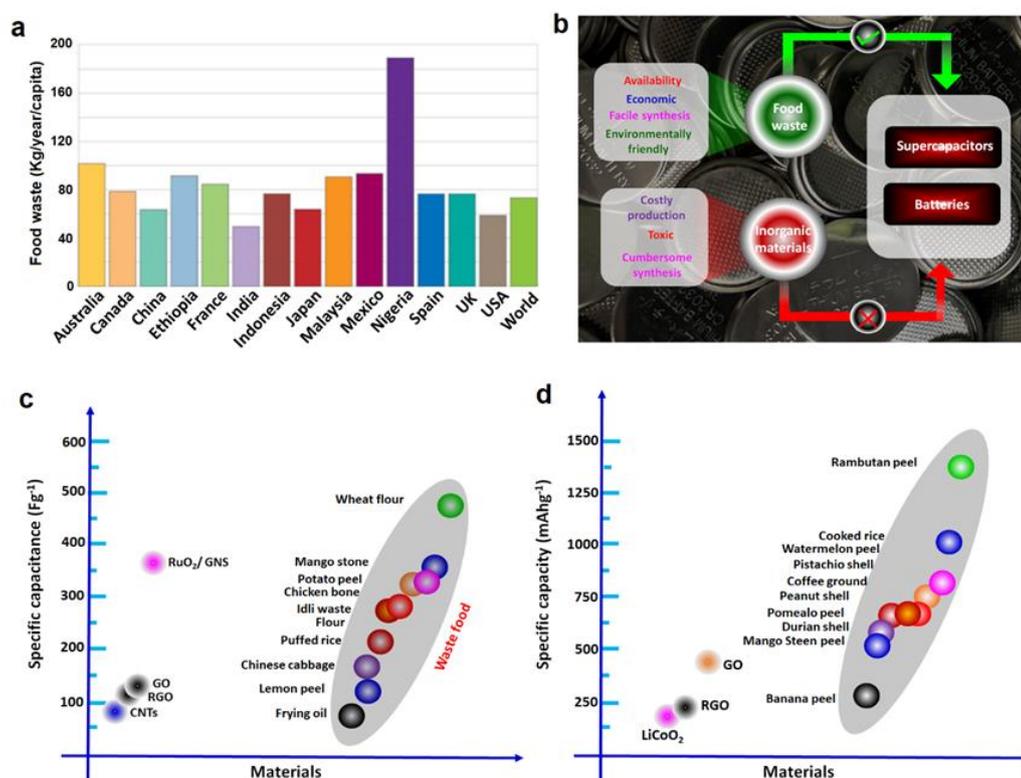
S. No	Sample	Food waste used	Activating agent	Synthesis conditions (Temperature in °C/Time in hours)	Surface area (m <sup>2</sup> /g)	Applications Specific capacity (mAh/g)/specific capacitance (F/g)	Ref
1	RPC	Rambutan peel	KOH	900 (2 h)	2104	1275 mAh/g	[100]
2	PBG-S	Pomelo peel	KOH	800	23	638 mAh/g	[101]
3	PSA	Pistachio shell	phosphoric acid	800 (4 h)	1345	650 mAh/g	[102]
4	FW	Food Waste	KOH	800 (1 h)	2403	442 F/g at 0.5 A/g	[103]
5		Puffed Rice	KOH	750, 800, 850, 900 (1h)	3326	218 F/g	[104]
6	CNOs	Waste frying oil	KOH	800 (1 h)	1545	71 F/g at 2 A/g	[39]
7	WPP	Waste potato peel	KOH	750 (3 h)	1911.5	323 F/g at 1 A/g	[105]
8	(N-WPAC)	a watermelon peel-	KOH	High Temperature	782.69	748.9 mAh/g	[106]
9	BPW	Banana Peel Waste	ZnCl <sub>2</sub> , H <sub>3</sub> PO <sub>4</sub> and KOH	700 (1 h)	815	272 mAh/g	[107]
10	Bcc	Chinese cabbage	KOH	900	778	171 F/g	[108]
11	LPC	Lemon Peel	No activation	800		121 F/g	[109]
12	CRC	cooked rice	KOH	900	1899	1006 mAh/g	[110]
13	WCG	waste coffee grounds	KOH	700 (2 h)	1622.77	175 F/g at 1 A/g	[111]
14	PS	peanut shells		300	38	778 mAh/g	[112]
15		waste-mango stone	ZnCl <sub>2</sub> /KOH	800 (1 h)	1497.8	353.8 F/g at 0.5 A/g	[113]
16	CCBW	Cooked chicken bone waste	KOH	700	2235.8	329.41 F/g	[114]
17		Bread-waste	KOH	850	610	202 F/g at 1 A/g	[115]
18		Idli wastes	KOH	650 (1 h)		280 F/g at 1 A/g	[116]

19	PTS	potato wastes	HCl	900 (3 h)	2201	54 F/g at 0.5 A/g	[117]
20		Hazelnut shell	HCl	1400 (3 h)		342 mAh/g	[118]
21	HPC	wheat flour	KOH	700 (2 h)	1313	473 F/g at 0.5 A/g	[119]
22		mangosteen peels	KOH	800	3244	509 mAh/g	[120]
23	4DPC	Durian shell	KOH	800	3215	604 mAh/g	[121]
24	FBC	Flour-based carbon	KOH	800 (1h)	1516	278 F/g at 2 A/g	[122]
25		Rice husk	KOH	750 (2 h)	769	220 mAh/g	[123]
26	WCG	Waste Coffee grounds	KOH	700 (2 h)	1355	650 mAh/g	[124]

**Table 2.** Compositional analysis of various food items in waste food.

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

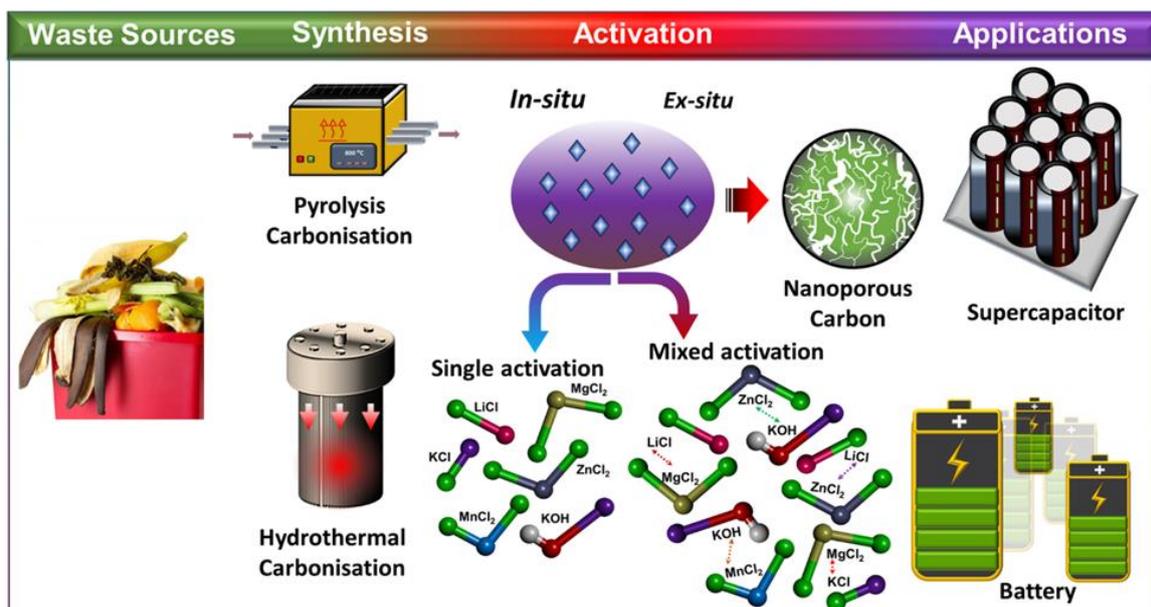
## Figures



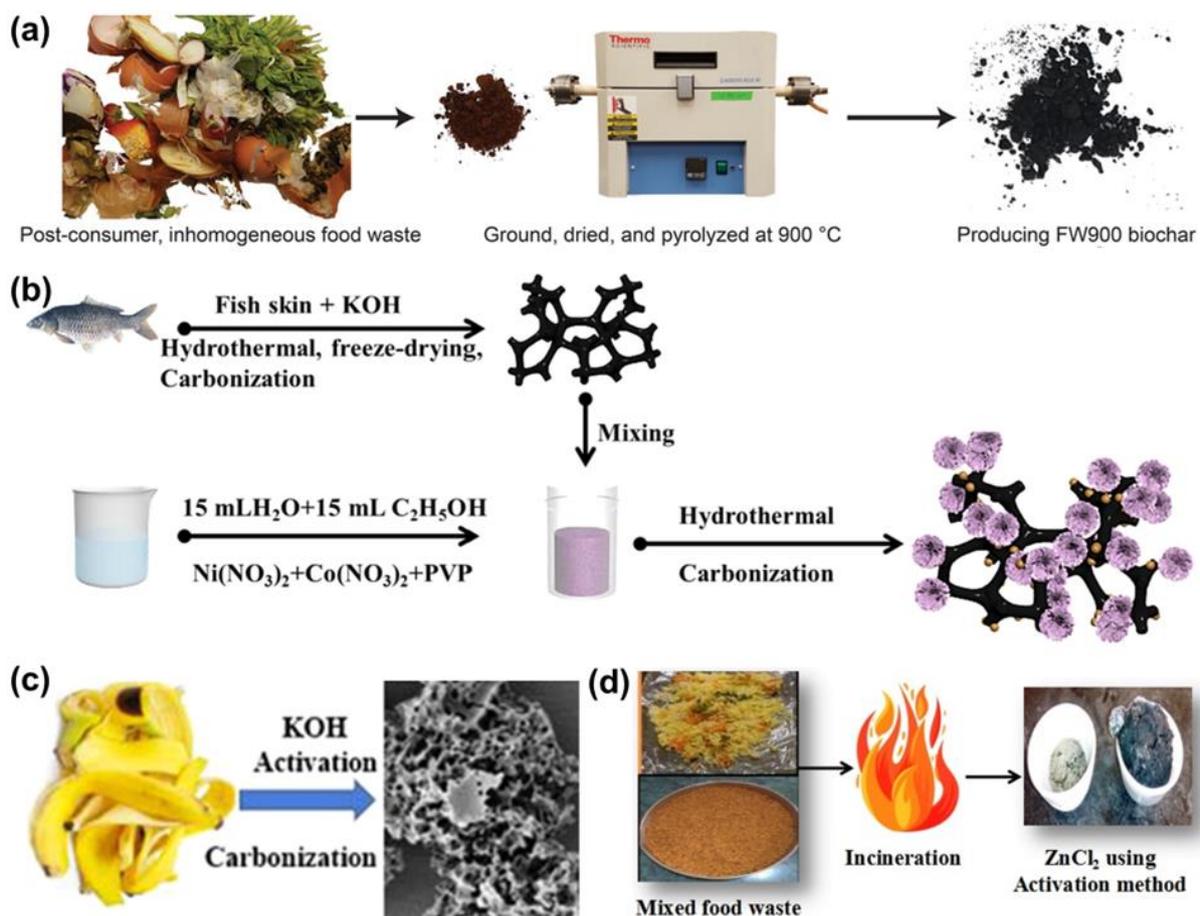
**Figure 1.** a) Country wise food waste (kg/year/capita), b) Potential energy storage applications of food waste vis-a-vis inorganic materials, c) Reported specific capacitance values for food waste and other inorganic materials, d) Reported specific capacity values for food waste and for other inorganic materials.



**Figure 2.** Advantages of waste food-derived nanoporous carbon as a source for energy storage devices.



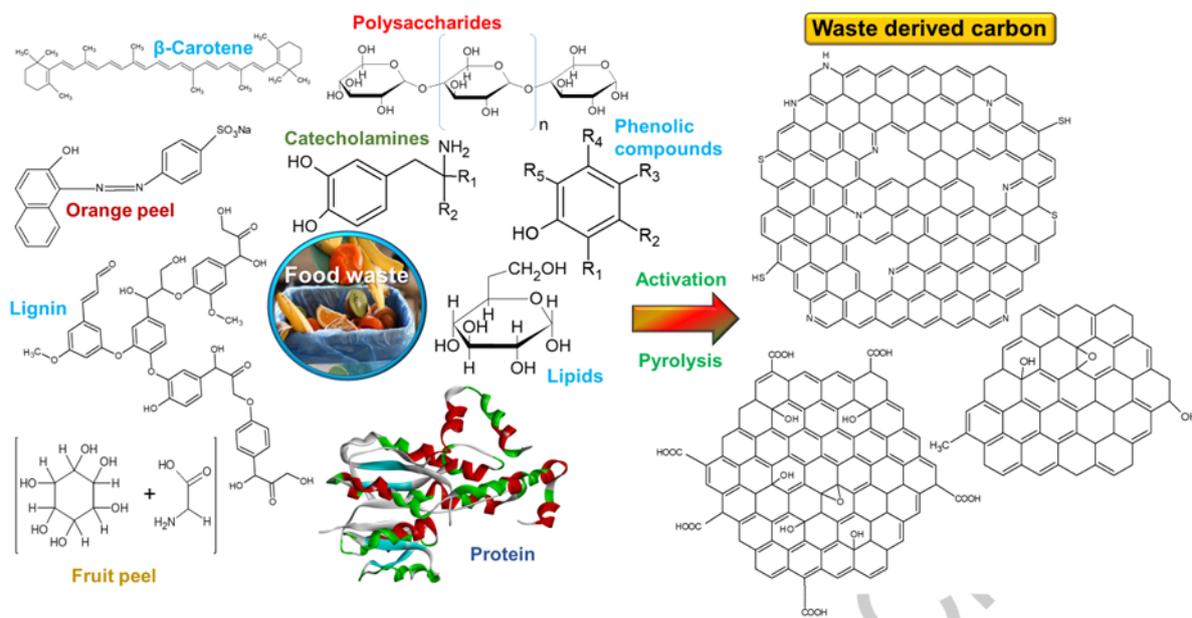
**Figure 3.** Strategies for synthesis, activation and energy storage applications of waste food derived nanoporous carbon.



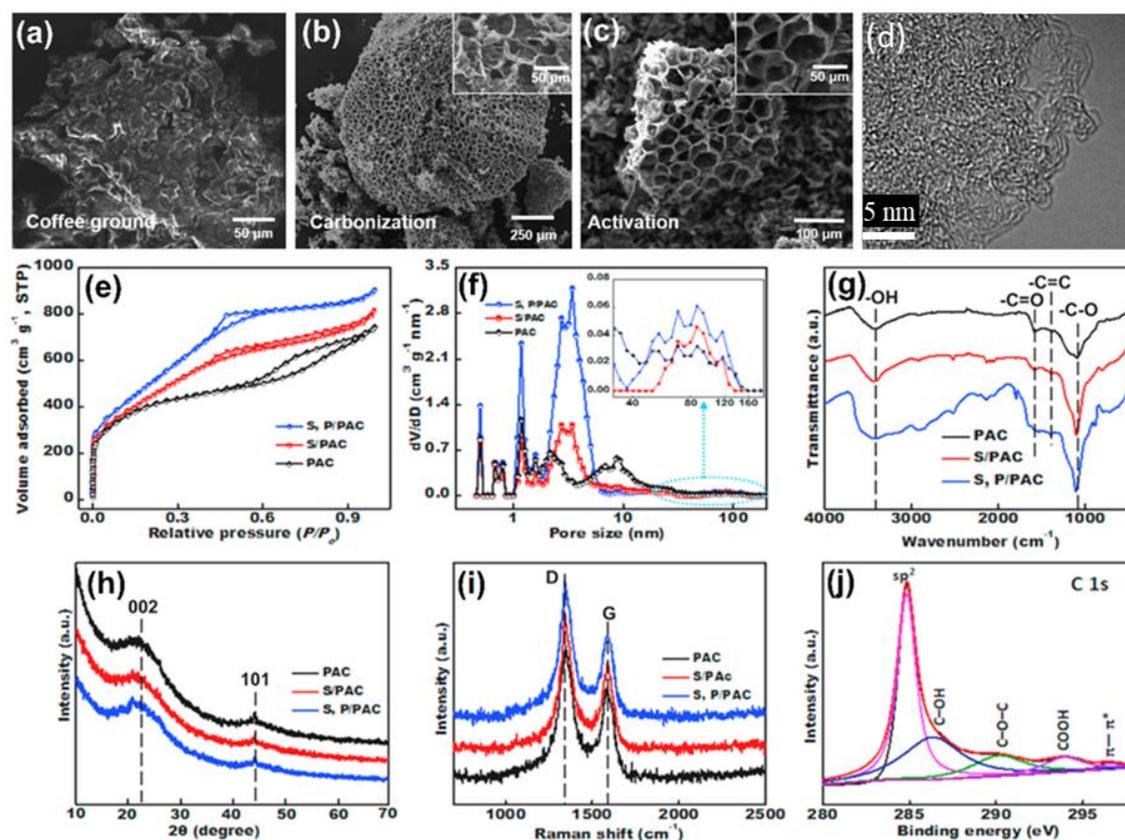
**Figure 4.** a) Conversion of post-consumer food waste into porous carbon using carbonisation/pyrolysis, reproduced with permission from [131] b) chemical activation of fish skin with KOH to produce porous carbon and its hybrid with NiCo/CoNiO<sub>2</sub>, reproduced with permission from [136] c) banana peel based porous carbon derived via chemical activation with KOH, reproduced with permission from [137] and d) porous carbon derived from food waste using zinc chloride based chemical activation reproduced with permission from [138].



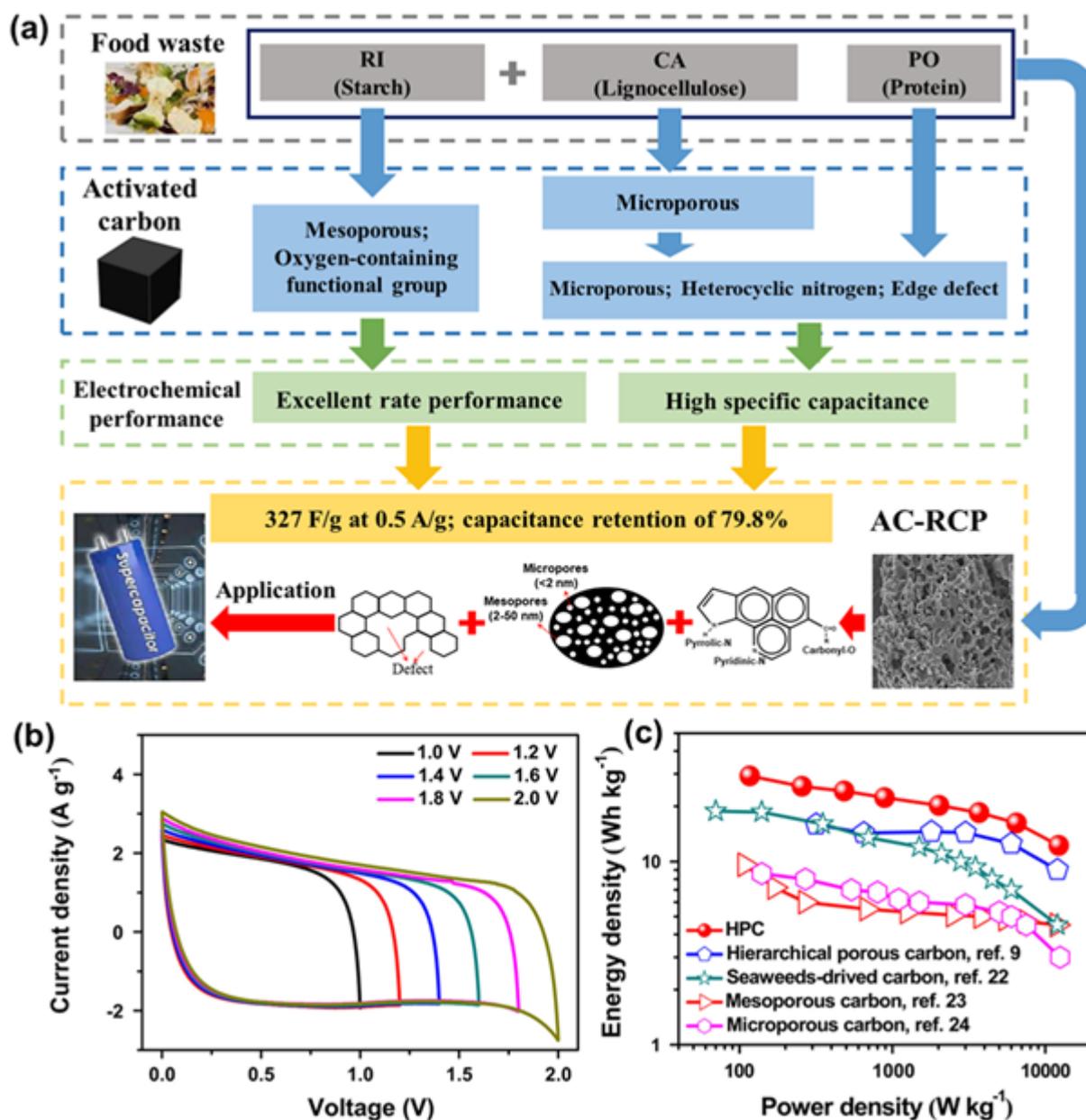
**Fig 5.** a-c) Steam based physical activation to convert food waste into porous carbon, the morphology of biochar and porous carbon, reproduced with permission from [141] d) Conversion of bread waste into hierarchical porous carbon via CO<sub>2</sub> activation, reproduced with permission from [115] and e-h) hydrothermal carbonization of oil extraction food waste (OEFW) for the production of hydrochar, reproduced with permission from [142].



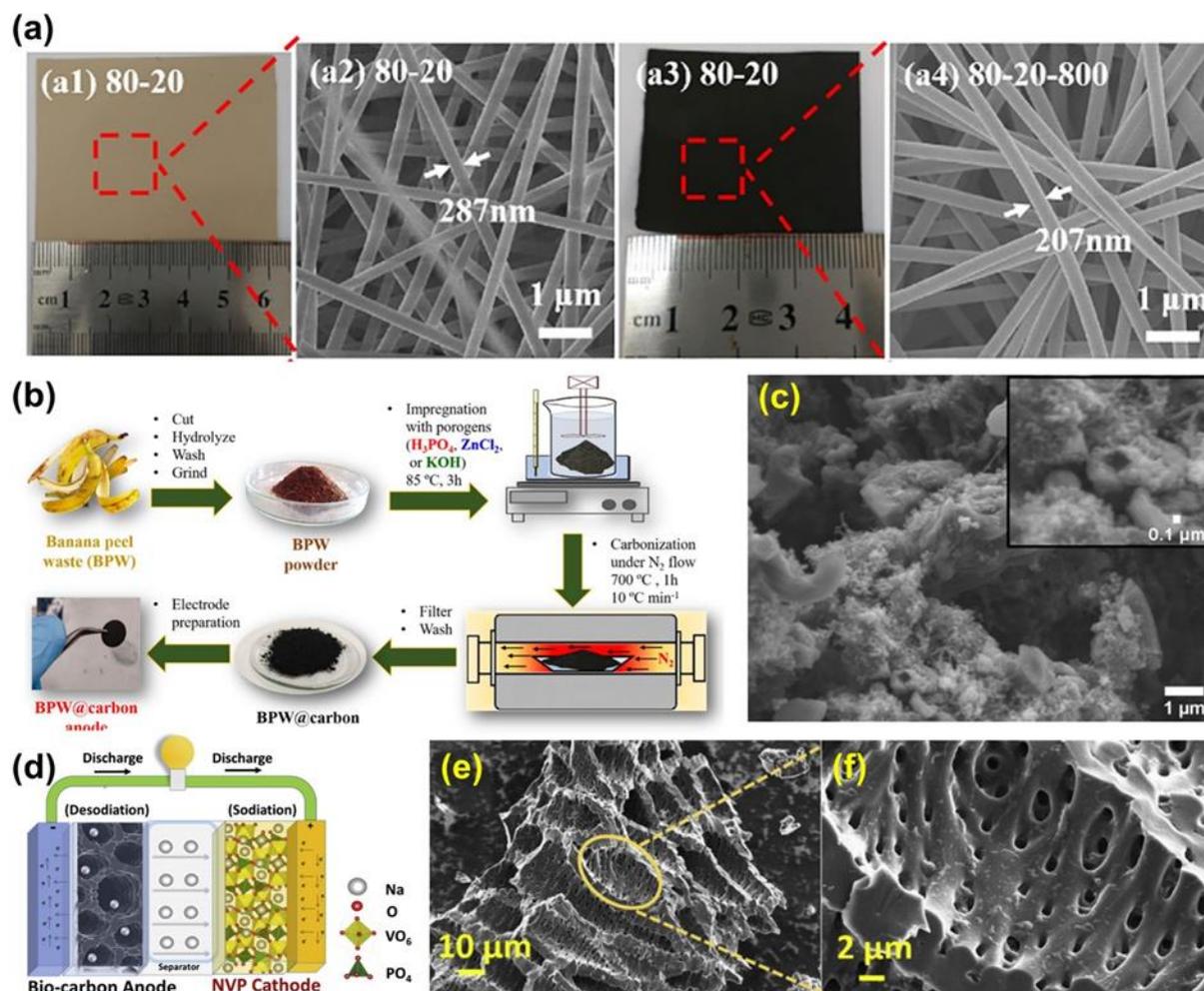
**Figure 6:** Possible molecular structure of the food waste starting precursors and the carbon synthesised from them.



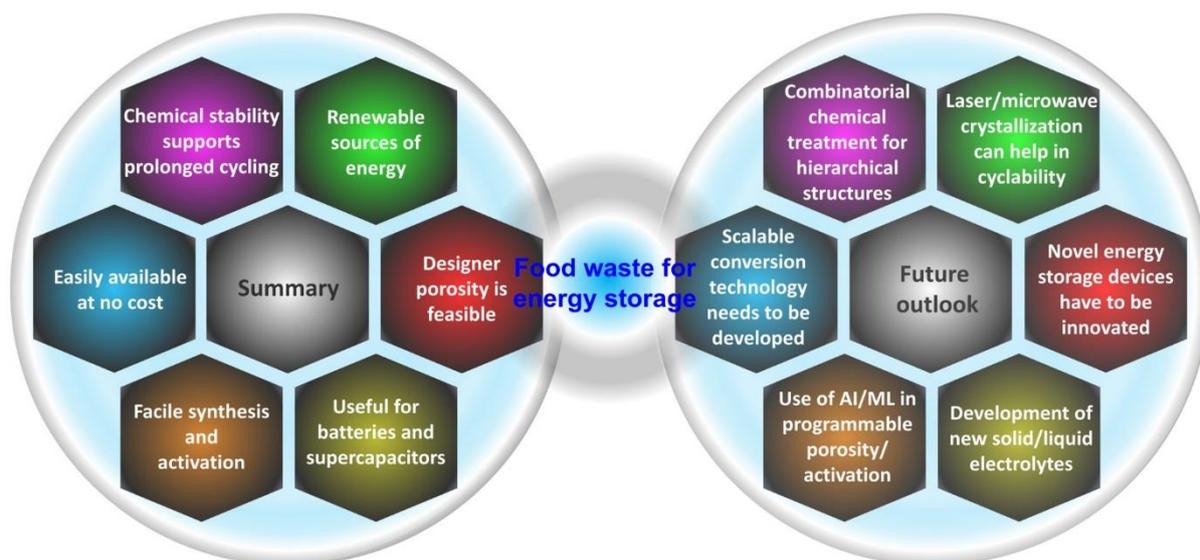
**Figure 7.** Experimental tools for characterizing nanoporous carbon: a, b,c, reproduced with permission from [124] SEM, d) TEM (inset shows HRTEM image and atomistic line profile), e) N<sub>2</sub>/O<sub>2</sub> adsorption/desorption curve (area under the curve gives surface area), f) DFT pore size (peak provides pore diameter), g) FTIR spectra (dips signify surface functionalities), h) XRD patterns (for identification of crystallographic planes), i) Raman spectra (D peak indicates defects and G peak indicates -C=C bonded crystalline order) and j) XPS spectrum (deconvoluted peaks indicate various bonding), reproduced with permission from [105].



**Figure 8:** a) Relationship of food waste with their electrochemical properties.[157] b) Operating voltage window of the supercapacitor device obtained from alkali treated flour activated carbon, c) Ragone plot of different symmetrical supercapacitor compared with the flour derived activated carbon, reproduced with permission from [119].



**Figure 9.** a1, a2) Photographs and TEM image of electrospun nanofibers mats, (a3, a4) Photographs and TEM image of carbon nanofiber mats, b) illustration of synthesis process for BPW carbon anodes, c) SEM images of BPW@KOH d) Schematic presentation of biocarbon/NVP full cell prototype, e, f) the FESEM image of the as-prepared biocarbon samples, reproduced with permission from [107,168,170].



**Figure 10.** Summary and outlook.

## Biographical note



Jefrin Marykala Davidraj is a PhD student at the Global Innovative Centre for Advanced Nanomaterials at the University of Newcastle. Her PhD work is focused on the development of porous carbon-based materials for application in the energy storage field.



Clastinruselraj Indirathankam Sathish is a post-doctoral fellow at the Global Innovative Centre for Advanced Nanomaterials at the University of Newcastle. His main research interest is the development of magnetic and porous materials and utilising them in various energy and environmental fields.



Mercy Rose Benzigar worked as a post-doctoral fellow at the Global Innovative Centre for Advanced Nanomaterials at the University of Newcastle. Her main research pursuits are in the field of porous materials for various applications in energy-related fields.



Zhixuan Li is pursuing PhD at the Global Innovative Centre for Advanced Nanomaterials at the University of Newcastle. Her research major is the development of novel 2D materials for various energy-related catalytic reactions.



Xiangwei Zhang worked as a visiting research scholar at the Global Innovative Centre for Advanced Nanomaterials at the University of Newcastle. His main research endeavours include dye degradation using porous materials.



Rohan Bahadur is a post-doctoral fellow at the Global Innovative Centre for Advanced Nanomaterials at the University of Newcastle. He primarily works on BCN-related porous materials for energy applications.



Kavitha Ramadass is a research fellow at the Global Innovative Centre for Advanced Nanomaterials, at the University of Newcastle. Her research interests focus on the design of multifunctional nanoporous materials for energy and environmental applications.

Gurwinder Singh  
for Advanced  
Australia. His  
and their



is a Research Fellow in the Global Innovative Centre for Advanced Nanomaterials at the University of Newcastle, research primarily focuses on nanoporous materials utilisation in various energy and environmental fields.



Jiabao Yi is a professor at the Global Innovative Centre for Advanced Nanomaterials at the University of Newcastle, Australia. His research focuses on oxides and oxide-based magnetic semiconductors, 2D materials and their magnetic properties, soft and hard magnetic materials, and magnetic nanoparticles for bioapplications.



Prashant Kumar is a senior lecturer at the Global Innovative Centre for Advanced Nanomaterials at the University of Newcastle, Australia. He has exploited these advanced quantum materials as well as their doped and hybrid versions in various frontline applications in electronics, optoelectronics, gas/molecular/strain/light ultrafast sensing, brain-computer interface, energy generation/storage and catalysis.



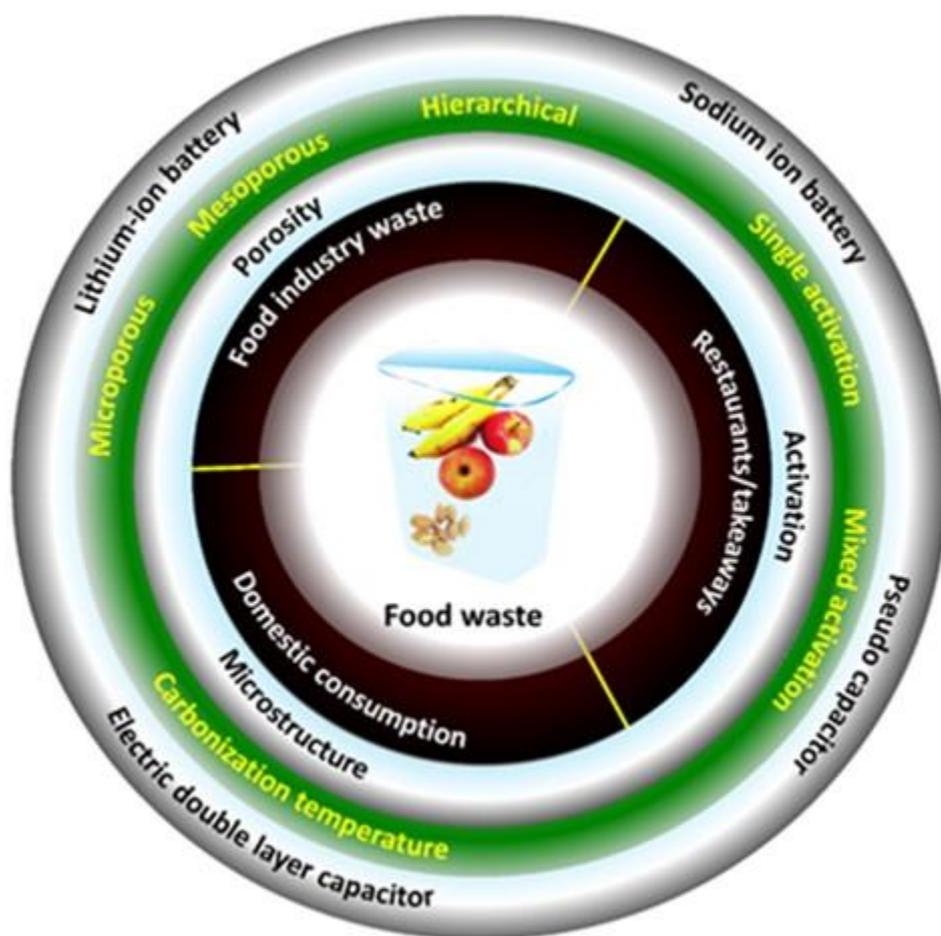
Prof. Ajayan Vinu is a Professor and the Director of GICAN at the University of Newcastle. He was previously working as a full professor and ARC Future Fellow at the University of South Australia and the University of Queensland. Before coming to Australia, he had been working as a research group leader at the National Institute for Materials Science in Japan. His research is mainly focused on developing new approaches to create nanoporosity in carbon nitrides, conducting polymers, metal nitrides, metal silicates, graphenes, silicas, sulfides, fullerenes, and biomolecules with

tunable structures and pore diameters and their potential applications in energy, environmental, biomedical and catalysis technology.

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This review compiles very recent literature on the synthesis of porous carbon from food waste biomass and their efficient utilisation as electrode material for energy storage applications in supercapacitor devices.

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