

## Challenges and perspectives of biochar anodes for lithium-ion batteries

Dimitra Vernardou<sup>a,\*</sup>, Georgios Psaltakis<sup>a</sup>, Toshiki Tsubota<sup>b</sup>, Nikolaos Katsarakis<sup>a</sup>,  
Dimitrios Kalderis<sup>c</sup>

<sup>a</sup> Department of Electrical and Computer Engineering, School of Engineering, Hellenic Mediterranean University, Heraklion 71410, Greece

<sup>b</sup> Department of Materials Science, Faculty of Engineering, Kyushu Institute of Technology, 1-1 Sensuicho, Tobata-ku, Kitakyushu 804-8550, Japan

<sup>c</sup> Department of Electronics Engineering, Hellenic Mediterranean University, Chania, Crete 73100, Greece

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### ABSTRACT

This perspective explores the applications and potential use cases of biochar anode in Lithium Ion Batteries (LIBs). The advantages as well as the challenges are investigated and compared to conventional materials such as graphite. We explore the synthesis and processing methods, focusing on its integration potential in LIBs with enhanced stability and capacity as showcased by recent studies. We also address the scalability challenges, the industry integration challenges as well as the environmental benefits of biochar anodes. Through this analysis it becomes evident that biochar is positioned as a promising alternative for efficient storage of energy that's also sustainable. This creates the path for future research to showcase its importance and realize its true potential as an anode material.

### Introduction

In order to identify sustainable and efficient energy storage solutions for the future, the exploration of novel materials and technologies capable of meeting the growing demands for new novel energy sources has been in the spotlight [1]. Among these, lithium-ion batteries (LIBs), stand out, as pivotal components in the energy landscape powering, almost everything from portable electronics to electric vehicles [2,3]. Traditional anode materials used in LIBs, for example graphite can reversibly intercalate lithium ions during the charging process with a theoretical capacity of 372 mAh g<sup>-1</sup> [4] due to its layered structure being sufficient to accommodate Li<sup>+</sup> [5]. Nevertheless, carbon black and graphite can induce significant environmental and economic challenges [6,7], contributing to CO<sub>2</sub> emissions of 4.4 and 2.4 kg, respectively [8]. It is therefore important to explore environmentally sustainable alternatives with less dependence on chemicals derived from fossil fuels.

Extensive research has been performed to explore materials and processes for replacing graphite with biochar as a renewable source. Graphite is typically produced from carbon-rich precursors, such as anthracite and petroleum coke, through energy-intensive graphitization processes [9]. In contrast, biochar-derived carbon materials are more widely available and exhibit naturally diverse structures. Additionally, they possess unique physical and chemical characteristics, including a large surface area [10] and micro- or mesoporous structures, which

promote the movement and exchange of ions [11]. Notably, the abundant porosity facilitates electrons and Li<sup>+</sup> diffusion, while the heteroatom-rich (N, O, S) of biochar allows the fine-tuning of the electronic structure [12] (i.e. enhancement of conductivity and introduction of active sites for various reactions). These distinct structures and morphologies provide unique performance characteristics compared to those of graphite, making it possible to achieve a specific capacity of 200–800 mAh g<sup>-1</sup> after 100 charge/discharge cycles [13–15].

The conventional techniques for crafting carbon materials from biomass included high-temperature carbonization [16], hydrothermal processes [17], template-based methods [18], as well as physical [19] and chemical activation [20] processes. High-temperature carbonization produces biochar with stable structure and porosity, but it is energy-consuming and generates pollutants. On the other hand, hydrothermal process operates at lower temperatures yielding different functional groups, however it often results in lower carbon content and surface area. Template-based methods allow precise control over pore structure, but their complexity procedure can increase production cost. Physical activation is simpler and more cost-effective, enhancing porosity, although it can result in less control over surface functionalization. Finally, chemical activation achieves high surface area and fine-tuning of surface chemistry, but requires toxic chemicals and additional purification steps, making the production process complicate. Understanding the advantages and disadvantages of these methods is

\* Corresponding author.

E-mail address: [dvernardou@hmu.gr](mailto:dvernardou@hmu.gr) (D. Vernardou).

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important for optimizing biochar properties and developing sustainable preparation strategies.

Depending on the type of biomass, the resulting carbon material may have different structure, porosity and composition [21]. An analysis of the literature shows that various types of biomass can be used to prepare biochar as a negative electrode including rice processing waste [22], bamboo residues [23,24] and miscanthus [25,26]. In addition, factors such as preparation methods (i.e. temperature and duration of the pyrolysis, heating rate, catalysts used), composition and morphology, have been studied for their impact on biochar's characteristics [27–29]. For example, increasing the pyrolysis temperature results in a graphite-like structure of biochar, with higher carbon content, but reduced porosity, surface-active groups and heteroatoms. The pyrolysis rate also plays a great influence. Fast pyrolysis reduces the carbon and oxygen content, the production time and the biochar yield [30].

The perspective below searches into the challenges and the possibility of integrating biochar as an anode material in LIBs, exploring its potential to revolutionize the energy storage industry [31]. It aims to provide a comprehensive overview of the current challenges, status and future prospects of biochar as anodes for LIBs, examining the latest advancements in material source including rice processing waste, bamboo residues and miscanthus. In addition, it explores the pathways to overcome those limitations and focuses on the economic feasibility as well as the scalability and the environmental impact for the integration in LIB production.

## Challenges

### Material synthesis, processing and electrochemical properties

One of the main underlying challenges that exist on biochar electrodes and especially anodes is definitely material synthesis and processing (Table 1). The primary hurdle in material synthesis is achieving uniformity in biochar's quality [32], a complex task due to the variability in biomass feedstock from cotton stalk [15] and bamboo [25] to rice husk [33] and miscanthus [26]. All these different materials once processed under pyrolysis have varied characteristics [34]. For instance, biochar obtained from cotton stalk exhibits notable characteristics, including its carbon content, surface area and porosity, making it a feasible candidate for anode material. Regarding the bamboo, it allows efficient biochar production with tailored properties for electrodes such as silica content, surface area and porosity. Despite rice husk's elevated ash content, it demonstrates surface area and porosity, influencing ion diffusion kinetics and charge storage capabilities. In terms of miscanthus, it is characterized by cellulose content (43.2–55.5 %) [35], which is important for its suitability in electrode materials. In addition, the high-yield biomass production potential of miscanthus holds promise in scaling biochar production.

Another significant parameter that affects the final characteristics of the produced biochar is the pyrolysis conditions including the duration for which the feedstock undergoes the pyrolysis process and the temperatures it reaches during this phase. The pyrolysis process can occur at different heating rates, resulting in various physicochemical properties [36]. Some feedstocks (i.e. bamboo, miscanthus) prefer higher temperatures like above 700 °C to become highly carbonized, create a high surface area and even increase their conductivity, while other feedstock (i.e. biomass feedstocks with high ash content) might have the opposite

results in such temperatures such as the formation of undesirable by-products or their degradation. This adds an additional degree of variability for the material processing of biochar [36].

Another critical aspect is the biomass composition, which requires treatment through Torrefaction Combined Treatment (TCT) before undergoing the carbonization process to enable their maximum potential. TCT is a method to pretreat the biomass at lower temperatures compared to other methods like pyrolysis. In specific, it involves heating the biomass in the absence of oxygen at temperatures typically ranging from 200 °C to 300 °C [37]. On the other hand, other biomasses might perform better under the Hydrothermal Carbonization (HTC) process. It is a type of wet torrefaction conducted at relatively low temperatures (180 °C to 250 °C) under self-generated pressure by heating biomass in the presence of water. These processes undergo the breakdown of biomass components through hydrolysis, decarboxylation, and polymerization, resulting in a solid product (hydrochar) [38]. These conditions affect the electrochemical performance of biochar having difficulties in reaching uniformity and consistent performance when implemented in a battery.

To improve their surface area and porosity, biochars are often activated through physical or chemical processes. A significant challenge is the activation method utilized in order to achieve the desired porosity and surface area for the improvement of the biochar's electrochemical properties [39,40]. The reasons why it can be challenging are related with a comprehensive approach involving material science, chemistry and engineering to refine the activation process and customize properties such as conductivity, surface area, heterogeneity, stability, cost and scalability). Overcoming such challenges, a multidisciplinary approach is imperative. This approach facilitates progress in material science to deepen our understanding of biomass properties, processing techniques and resulting biochar characteristics. Special attention is required to give on the electrochemical attributes of biochar anodes, such as lithium-ion storage capacity, rate capability, and cycling stability, which are intrinsically linked to the material's synthesis and activation processes [39,41]. For instance, the activation of biochar using steam or carbon dioxide at high temperatures enhances its porosity and surface area, crucial factors for facilitating lithium ion diffusion and electron transport [42,43]. Examples like this highlight the need for optimized synthesis protocols. Crafting standardized production methodologies that can adapt to this variability are crucial for the scalability and commercial viability of biochar anodes. Investigating innovative pyrolysis methods, such as microwave-assisted pyrolysis or catalytic pyrolysis and improving the consistency and quality of biochar [44] can also guide to the optimization of biochar. Similarly, employing advanced material characterization techniques could shed light on the microstructural changes induced by different synthesis conditions. This information can then help to the optimization of biochar and the improvement of electrochemical performance, paving the way for the integration of biochar anodes into the next generation of LIBs. This will mark a significant stride toward sustainable energy storage solutions [45].

### Scalability, industrial application and integration with existing battery technologies

Addressing the scalability and industrial application of biochar anodes for LIBs, is crucial for any kind of success for biochar in the market

**Table 1**  
Summary of biochar production methods and their impact on electrochemical properties.

Biomass Feedstock	Pyrolysis Conditions	Pretreatment Methods	Activation Process	Impact on Electrochemical Properties	References
Cotton Stalk	Varied temperatures, often > 700 °C	TCT at 200 °C–300 °C	Steam or CO <sub>2</sub> activation	Enhances porosity and surface area	[15,16]
Bamboo	Incremental temperature increases	HTC at 180 °C–250 °C	High temperature processes	Affects capacity and stability	[25]
Rice Husk	Tailored duration and temperature	Not specified	Activation for carbon layers	Improves functionality and porosity	[22,33]
Miscanthus	High temperatures for carbonization	Not specified	Not specified	Influences storage capacity and conductivity	[26,35]

share. The scalability lies in transitioning from laboratory-scale experiments to mass production, a leap with a plethora of challenges unique to the industrial context [46]. A main concern is the integration of biochar anode production into existing manufacturing infrastructure [47]. Traditional LIB production lines are optimized for conventional anode materials like graphite [6]. However, in order to adapt these lines for biochar, significant logistical and technical issues should be addressed. Among these issues, is the variability in conditions for each feedstock of biochar per batch, needing flexible parameters each time [25,33]. This flexibility and adaptability is not usually found in conventional and current production lines that are optimized for large scale productions [48–50]. In addition, the economic viability of biochar is possible if the feedstock is sourced at a minimal cost [40]. Although, biochar holds promise for its potential to utilize waste biomass, the logistical challenges involved in collecting, transporting, and storing various biomass types can significantly impact production costs. Ensuring a consistent and reliable biomass supply chain is crucial for maintaining steady production rates and quality [51]. Critical aspects for the scalability are factors such as thermal stability, structural integrity and mechanical stability. Guaranteeing these qualities for mass production and prolonged operational life, is the key for industrial implementation [52,53]. Therefore, optimizing pyrolysis processes for every composite material and preparing them for scalability and economic feasibility, are paramount [54]. In addition, the interaction between biochar anodes and electrolytes significantly impacts the overall battery performance. The surface chemistry of biochar, including functional groups and porosity, can significantly affect the ion transport and the stability of the solid-electrolyte interphase (SEI) layer [55]. This interaction dictates lithium-ion diffusion rates, electrode wettability, and overall ionic conductivity within the cell. Repeated charge/discharge cycles can cause volume changes and mechanical stress on the anode material, underlining the importance of its structural integrity and mechanical stability [52]. Exploring methods like cross-linking biochar particles or creating composites with carbon nanotubes or graphene can offer improvements in this area [55,56]. The push towards higher energy densities in LIBs necessitates anodes that can match the capacity and voltage requirements of advanced cathode materials. The compatibility, alongside the ability to sustain high loads and avoid capacitance, requires further research.

It is necessary to consider the unique properties of biochar [31] to design new LIBs. The activation of biochar by steam or carbon dioxide to increase its porosity and surface area is crucial for lithium-ion diffusion and electron transport. Furthermore, the process of fabricating electrodes based on biochar differs from the conventional methods employed for graphite, which include the mixing biochar with a conductive agent and a binder, followed by applying the mixture on a current collector.

It is important not only to implement biochar anodes into existing battery manufacturing technology, but also to deal with issues concerning scalability and industrial applications. Integrating biochar into battery technology poses a significant obstacle, especially when it comes to economic considerations [57,58]. Innovation and collaboration among researchers and industry players are needed to address these aspects (Fig. 1).

Regardless the above challenges, biochar poses as an attractive alternative especially due to its economic benefits and the versatility of its electrochemical properties. The utilization of biochar, derived from abundant biomass sources, inherently reduces the cost associated with the production of anode materials for LIBs [41,59]. The year-round availability of biomass and the potentially low cost of acquisition results in an economic benefit in comparison to traditional anode materials [60]. Biochar typically produced from forest or agricultural residues and other plants such as cotton, bamboo and others, not only reduces the production cost, as already mentioned above, but also utilizes residues that would otherwise be considered waste and end up landfilled or burned in the open [61]. In addition, the production cost

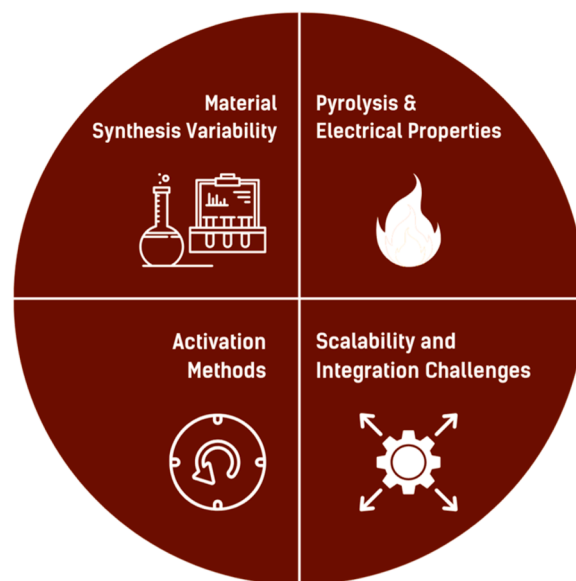


Fig. 1. The challenges of biochar as anode material for lithium ion batteries.

reduction of LIB and the promotion of a decentralized manufacturing process can be accomplished by producing biochar from local biomass. The economic viability of biochar anodes is based on the support of local economies and reduction of logistics and transportation costs associated with the supply chain [60,62]. Although the pyrolysis process used to produce biochar requires considerable energy, it can become energy efficient when coupled with bioenergy systems that harness the generated heat. Alternatively, it may produce valuable by products, such as bio-oils, which serve as valuable fuel sources [63]. The potential for biochar to improve the cycling stability and longevity of LIBs can result in lower lifecycle costs for end-users. Biochar's high surface area, achieved through activation processes, provides more active sites for lithium ion storage [39] potentially increasing the specific capacity of LIBs. These characteristics are crucial for facilitating lithium ion diffusion and electron transport, thereby improving the charge/discharge rates, energy density, and overall efficiency of LIBs. The variability in biochar's pyrolysis and pre-processing enables it to be tailored for specific electrode applications. Additionally, biochar's conductivity can be enhanced through doping with heteroatoms (such as nitrogen, boron, or phosphorus) [64] or combining it with conductive additives, improving charge transfer rates and, consequently, the battery's power density. For instance, the activation with steam or carbon dioxide, treated at specific conditions, plays a pivotal role in enhancing the lithium ion storage capacity of the biochar with studies showing differences in capacity of up to 27 % "The specific capacity was found to be for LSW-AC S = 600 mAh g<sup>-1</sup> while for LSW-ACC = 760 mAh g<sup>-1</sup>" [41]. Biochar anodes can also exhibit improved cycling stability due to their robust structure and ability to accommodate volume changes during the lithiation and delithiation processes [65]. The combination of economic and financial viability, along with the performance and efficiency improvements, positions biochar as a compelling prospect for the next generation of LIBs.

A quantitative analysis of the scalability and economic viability of biochar compared to graphite explores factors including raw materials availability, production costs, energy requirements and potential output capacity [66–71]. Biochar can be produced from different range of biomass sources, with an estimate indicating that over 1.3 billion tons of agricultural waste is produced each year, providing a substantial supply for production. On the other hand, global production of natural graphite was about 1.1 million tons in 2022, limited by the environmental impact of mining. Moving to the production cost, biochar ranges from \$30 to \$200 per ton depending on the type of source and processing method. In

comparison, natural graphite costs range between \$800 to \$2500 per ton, while synthetic graphite can exceed \$3000 per ton because of the large energy-consuming processing steps. Biochar production by pyrolysis require 5 to 10 GJ per ton with the enhancement of sustainability via the exploitation of waste heat or renewable energy. In contrast, natural graphite (in terms of extraction and processing requirements) needs more energy, in the order of 15 to 25 GJ per ton, while synthetic graphite demands over 30 GJ, thereby having a larger carbon footprint than biochar. Small-scale biochar can be produced between 1 and 10 tons per day, and large-scale facilities can produce 50 to 200 tons per day, due to the design that allows flexible scaling. Large graphite mines can produce thousands of tons per day, but high capital investment hinders scalability. Overall, biochar is more scalable than graphite because more raw materials are available due to lower production costs and the possibility of renewable energy integration.

#### Environmental impact, sustainability and safety

Biochar integration in LIBs is a step forward for environmental sustainability and safety. Biochar is an eco-friendly carbonaceous, at the forefront of this green revolution [72,73]. The utilization of renewable resources, such as agricultural waste and forestry residues, is the foundation of a sustainable innovation for the reduction of carbon emissions [7,74]. Deploying biochar in LIBs has an environmental impact on the reduction of greenhouse gas emissions and the promotion of waste valorization. Furthermore, the pyrolysis process of biochar reduces carbon dioxide emissions [75], thus reducing landfill burden and transforming waste into resources, in line with the basic principles of the circular economy [76].

In addition, through the utilization of biochar, sustainability and safety are enhanced offering a greener alternative that reduces soil/water pollution, unlike traditional anode materials with diverse environmental impacts. Conventional materials, upon reaching the end of their lifespan, generate environmentally hazardous waste, with elements such as nickel/cobalt posing health risks and causing water pollution. In addition, the extraction and processing of materials like nickel and cobalt are associated with significant health risks, including respiratory diseases, water pollution, and other environmental health impacts [77,78]. Especially in comparison to carbon black, which relies on non-renewable fossil fuels and poses concerns regarding resource depletion and environmental degradation [74], biochar offers a more sustainable alternative. Additionally, its superior thermal stability and resistance to degradation enhance the overall safety profile of LIBs, mitigating risks such as thermal runaway and electrolyte leakage. This property is essential for the expansion of lithium batteries in a variety of fields such as energy storage etc. especially in fields where safety is considered of highest priority.

The potential of biochar anodes in lithium batteries goes beyond simple techniques for performance improvement and involves a holistic approach to managing environmental impact and safety. If we harness the potential of biochar, we can say that biochars aid in reducing the carbon footprint of energy storage systems, but also enhance waste management practices and foster safer energy solutions (Fig. 2).

A comprehensive comparison between graphite and biochar in terms of sustainability and safety can be accessed through various metrics, including carbon footprint, energy consumption, raw materials availability and health impacts. While natural graphite production has large carbon footprint, biochar is characterized by its potential capacity to sequester data the atmospheric CO<sub>2</sub> and a negative carbon footprint. Its energy requirements (range from 5 to 10 GJ per ton) are significantly lower, typically using energy sources or waste heat that makes its carbonization sustainable [79,80]. This compares to natural graphite production (15 to 25 GJ per ton-depending on flake size) and synthetic graphite demands 30 GJ per ton [81]. Given the availability of raw material, biochar can be produced sustainably from billions of tons of biomass annually versus graphite production limited to millions of tons



Fig. 2. The prospects of biochar as anode material for lithium ion batteries.

due to environmental regulations and finite resources. These metrics are key to consider in production process scalability. Some natural and synthetic graphite production, along with the processing of both types of materials, which can produce dangerous emissions or introduce potentially toxic substances into the environment via solid or liquid waste disposal, have significant adverse safety metrics. On the other hand, the production of biochar is generally considered as safe and less toxic [82]. This waste biochar does not contain harmful chemicals and no polluting gases are generated during the production process. Concerning mining operations for graphite can bring about dangerous workplace conditions, such as dust exposure and possible accidents. The regulation around mining unfortunately does not always guarantee that the workers involved in extracting one of our most important resources will actually be safe. Overall, the quantitative analysis of risk suggests that biochar is superior to graphite in sustainability and safety. Low carbon emissions, minimal energy requirements and an abundance of renewable resources make it a strong case in the market for anode materials. In addition, the safe production process makes biochar an eco-friendly choice. These factors are effectively shown in Fig. 3, providing a clear representation of the comparative benefits of biochar.

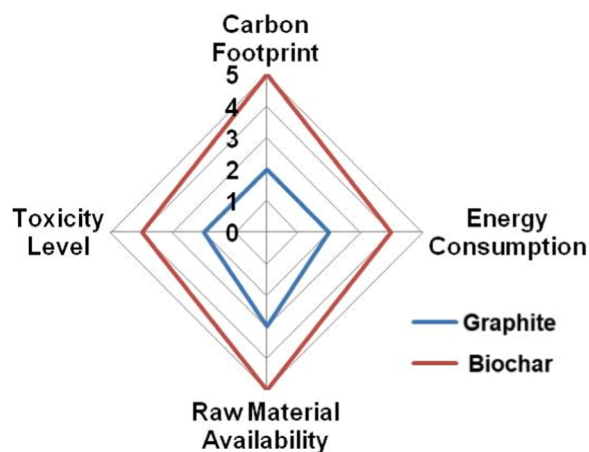


Fig. 3. Radar plot indicating the benefits of biochar over graphite, emphasizing its lower carbon footprint, reduced energy consumption, greater availability of raw materials and lower toxicity levels.

## Advances in biochar anodes

Expanding upon the challenges and prospects of biochar, particularly as anodes in LIBs, it is crucial to explore some recent advancements in biochar anodes to understand the current landscape of research. A research study introduced a novel approach to LIBs by employing activated tannery waste biochar as an anode, achieving a remarkable specific capacity of  $760 \text{ mAh g}^{-1}$ . In this study, researchers demonstrated the efficacy of biochar electrodes activated via two distinct methods: steam activation of metal-free leather shaving waste (LSW-ACS) and  $\text{CO}_2$  activation (LSW-ACC). Remarkably, the  $\text{CO}_2$  activation process notably enhanced the final specific capacity of the electrode, increasing from an initial discharge capacity of 2063 to a retained  $760 \text{ mAh g}^{-1}$ , while steam activation initially yielded  $1520 \text{ mAh g}^{-1}$ , stabilizing around  $610 \text{ mAh g}^{-1}$  thereafter (Fig. 4(a)). Meanwhile, electrodes made from biochar without any activation exhibited a performance ranging from  $500 \text{ mAh g}^{-1}$  initially, declining to approximately  $380 \text{ mAh g}^{-1}$  after 80 cycles at  $0.1 \text{ A g}^{-1}$ . This proves that the activation processes lead to the enhancement of reversible Li-ion storage by altering the surface properties of the biochar such as surface texture (Fig. 4(b)-(d)). This method not only demonstrated a substantial increase in lithium storage capacity, but also ensured sustained performance over 1500 charge/discharge cycles, showcasing a notable improvement in the durability and efficiency of biochar-based anodes [41]. In another recent study, researchers tailored cotton stalk biochar particle size to enhance structural qualities and lithium diffusion efficiency. A cotton stalk biochar with particle size in the range of  $450$  to  $2000 \mu\text{m}$  (CSC2), resulted in  $400 \text{ mAh g}^{-1}$  capacity after the 2nd cycle (Fig. 4(e) and (f)), which retained a value of  $229.7 \text{ mAh g}^{-1}$  over 100 cycles [15], surpassing the capacity of traditional graphite and highlighting the potential of biochar. Additionally, a study has improved LIB anodes through the conversion of *Aspergillus Niger* fermentation residues into nitrogen/silicon-enriched biochar. This innovation showcased superior electrochemical performance and enhanced stability when compared to conventional carbon anodes. Specifically, the *Aspergillus Niger* Carbon (ANC) exhibited a charging capacity of  $346.9 \text{ mAh g}^{-1}$  (Fig. 4(g) and (h)). This proves the potential of fungal biomass for the production of high performance and sustainable anodes [83]. Biochar has also been integrated in silicon-based anodes for LIBs using phosphorus-doped biochar cotton fiber to form a 3D conductive network, yielding promising results with enhanced conductivity and structural integrity. In particular, the Si@P-doped carbonized cotton fiber (Si@PCCF) electrode initially had a

good capacity of  $3700 \text{ mAh g}^{-1}$ , while also retained a good enough capacity of 47 % of its original values after 150 cycles, reaching a value of  $1777.15 \text{ mAh g}^{-1}$ . In comparison, the undoped Si@carbonized cotton fiber (Si@CCF) of the electrode only retained 34 % of its original specific capacity of  $3420 \text{ mAh g}^{-1}$  reaching a value of  $1162.8 \text{ mAh g}^{-1}$  after 150 cycles. It is important to note that the phosphorus doping was performed at  $350 \text{ }^\circ\text{C}$ . Phosphorous doping increases capacity, however it is important to compare these results with electrodes without carbonized cotton fiber. For instance, Si with graphite and pure Si electrodes will initially perform similar to undoped Si@CCF. However, they show poor capacity retention, with 20 % for the Si with graphite and 0 % for pure Si after 150 cycles. These findings highlight the biochar's stability [64]. In addition, a recent study showed that biochar is a promising and sustainable material for LIB anodes, with innovations that include biochar derived from  $\text{NCO}_2\text{CO}$ -enriched wood with enhanced performance, showing increased charge/discharge capacity of  $870/1735 \text{ mAh g}^{-1}$  from the LIB that did not contain biochar  $647/1132 \text{ mAh g}^{-1}$  [84]. Biochar has also been derived from lignite as a renewable source, a high-conductivity additive for LIB anodes, indicating promising performance comparable to carbon black. Biochar indicated similar performance to Super P with a capacity of  $329.2 \pm 1.4 \text{ mAh g}^{-1}$ , demonstrating greenhouse gas emission reductions (a decrease of 49 % in emissions compared to traditional carbon black.) [74]. Another research study focused on biochar-supported  $\text{Fe}_3\text{C}$  nanoparticles as high-performance binder-free anode material, with excellent electrical conductivity and a 3D macroporous structure. This resulted in higher interfacial contact and lower charge transport resistance with a notable power density of  $2316 \text{ mW m}^{-2}$  [85]. In another study, rice husk was used in the fabrication of an anode for lithium-ion batteries, and it showcased that the chemically modified rice biochar considerably improved battery and supercapacitor properties [22]. Those recent advances in the research of biochar electrodes for LIBs truly showcase how it will impact the research field emphasizing on its potential for environmental sustainability.

Table 2 shows the latest results focusing on the utilization of waste products as materials for the integration in anodes for LIBs. The influx of publications showcases a considerable shift in the industry towards more sustainable practices by reusing waste materials in LIBs. The documented results highlighted the efficacy of those sustainable methodologies for materials and electrode preparation underscoring the influence of the capacity values due to the varying biomass sources and preparation techniques. These specific variations are key towards

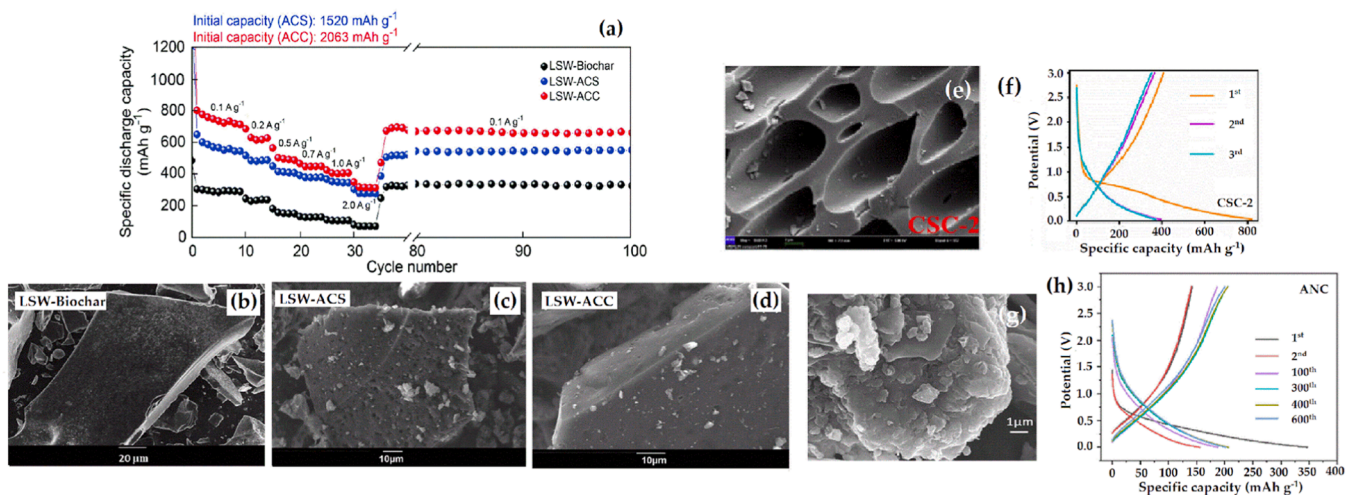


Fig. 4. (a) Rate capability at different current densities of the carbonized samples at  $0.1, 0.2, 0.5, 0.7, 1$  and  $2 \text{ A g}^{-1}$ . (b), (c) and (d) SEM images of LSW-Biochar, LSW-ACS and LSW-ACC, respectively. (f) SEM image and (g) charge-discharge profiles of CSC-2. (h) SEM image and (i) charge-discharge curves of ANC for a range of scan numbers.

Images adapted by permission from ACS (Ref. [19]), RSC (Ref. [27]) and Elsevier (Ref. [59]).

**Table 2**  
Comparison of treatment and capacity values for different biomass sources.

Biomass resource	Treatment	Reversible capacity (mAh g <sup>-1</sup> )/cycle number	References
Peanut shell	KOH activation	680/100	[86]
Cotton stalk	Pyrolysis	271.7/100	[15]
Spruce	H <sub>3</sub> PO <sub>4</sub> activation	156/150	[87]
Gingko leave	Pyrolysis	410/500	[88]
Seaweed	KOH activation	550/300	[89]
Agar	KOH activation	190/100	[90]
A. Niger mycelial residue	Pyrolysis	300.90/900	[83]
Tannery	CO <sub>2</sub> activation and steam activation	452/450 and 625/1500	[41]
Wheat straw	KOH activation	310/100	[91]
Garlic peel	KOH activation	540/100	[92]
Corn stalk core	KOH activation	504/100	[93]
Tea seed shells	KOH activation	537/100	[94]

understanding and therefore better guiding us to choose and prepare the most sustainable feedstock. This will ultimately contribute to a more efficient and sustainable utilization of our biowaste products.

## Conclusions

Biochar showcases promising properties that place it ideally to be considered as an anode material thanks to the added benefits of sustainability and cost effective energy storage solution. The inherent stability it brings in LIBs in addition to its porous nature, enhances capacity and makes it a standout material. It is able to facilitate efficiently the charge transfer process thereby improving the cycling stability of the batteries. Even though there are potential issues with the integration of existing battery technologies and the huge variability in material synthesis and processing methods, recent advancements showcase the potential for the enhancement of the overall performance of biochar. Reduced greenhouse gas emissions, use of waste byproducts and biomasses, along with the economic benefits associated with aligning biochar directly with the global sustainability movements, highlight its significant environmental and financial potential. In order to harness biochars full potential in the energy sector there is an imminent need for the future research to overcome its limitations through the use of novel material science protocols. As such, biochar anodes can emerge as a viable solution for improving the sustainability and efficiency of LIBs. This showcases an opportunity to reduce the environmental impact of energy storage technologies, while at the same time paving the way for a greener energy future.

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## CRediT authorship contribution statement

**Dimitra Vernardou:** Visualization, Validation, Supervision. **Georgios Psaltakis:** Writing – original draft. **Toshiki Tsubota:** Writing – review & editing. **Nikolaos Katsarakis:** Writing – review & editing. **Dimitrios Kalderis:** Writing – review & editing.

## Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used in some parts of the text AI-assisted technologies on the text toward improving the readability of the manuscript. The authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data Availability

Data will be made available on request.

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