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Algae-Based Hard Carbon as a Sustainable Replacement for Graphite Anodes in Lithium-Ion Batteries

Trisha Sadh, Department of Computer Science & Engineering, Indore Institute of Science & Technology, Indore, Madhya Pradesh, India trisha.sadhcse2024@indoreinstitute.com

Praveena Joshi, Department of Computer Science & Engineering, Indore Institute of Science & Technology, Indore, Madhya Pradesh, India praveena.joshi@indoreinstitute.com

Abstract: Graphite is the dominant anode material in commercial lithium-ion batteries owing to its high reversibility and excellent cycling stability. However, its limited theoretical capacity of 372 mah g^{-1} and environmental concerns associated with graphite mining motivate the search for more sustainable and higher-capacity alternatives. Biomass-derived hard carbons, particularly algae-based hard carbons, have emerged as promising candidates due to their renewable origin, tunable porosity, and rich surface chemistry. This paper reviews the synthesis routes, structural characteristics, lithium-storage mechanisms, electrochemical performance, advantages, and current limitations of algae-derived hard carbon anodes. Reported studies indicate that optimized algae-based hard carbons can deliver reversible capacities exceeding those of graphite and offer improved rate capability and low-temperature behaviour, while reducing dependence on mined or fossil-based carbons. Nevertheless, significant initial irreversible capacity loss, relatively low electronic conductivity, and challenges in large-scale, reproducible production still hinder practical implementation. Addressing these issues through surface engineering, heteroatom doping, and process optimization will be crucial to realize algae-derived hard carbon as a viable sustainable replacement for graphite in next-generation lithium-ion batteries.

Keywords: Algae-based carbon; Hard carbon anode; Lithium-ion batteries; Biomass-derived carbon; Sustainable energy storage; Porous carbon

1. Introduction

Lithium-ion batteries (LIBs) play a crucial role in today's energy storage, powering devices such as portable electronics, electric vehicles, and large-scale systems. Most LIBs use graphite anodes because they operate at low voltages, have high efficiency, and are relatively easy to manufacture. Still, graphite's maximum capacity is 372 mAh g^{-1}, which limits how much energy these batteries can store. Making battery-grade graphite also requires a significant amount of energy and can lead to environmental issues stemming from mining, purification, and transportation.

As a result, there is increasing interest in biomass-derived carbon materials as low-cost and sustainable alternatives to graphite. Among them, algae-based hard carbon is very promising because microalgae and macroalgae grow rapidly, can be cultivated in wastewater or poor-quality land, and absorb CO_2 during their growth. When algal biomass is pyrolysed under an inert atmosphere, it forms hard carbon with a disordered structure, hierarchical porosity, larger interlayer spacing, and many surface functional groups. These properties make it suitable for lithium storage. This study discusses the existing research gaps and examines the potential of algae-derived hard carbon as a sustainable replacement for graphite anodes in lithium-ion batteries.

2. Synthesis and Structural Characteristics

Algae-based hard carbon is typically produced by first drying the algal biomass and then carbonising it under a nitrogen or argon atmosphere at temperatures between 800 and 1200 °C. In some cases, chemical or physical activation is also used to control the pore structure. The resulting material has a non-graphitic, turbostratic structure composed of short-range ordered graphene layers that are randomly oriented and separated by nanopores and disordered regions. Because of its interconnected micro- and mesopores, high specific surface area, and larger interlayer spacing compared to graphite, this structure forms a three-dimensional, sponge-like framework.

Thus, algae-derived hard carbon contains more edge sites, defects, and internal cavities that can act as lithium storage sites compared to the highly ordered layered structure of graphite. In addition, residual heteroatoms from the algal precursor, such as N, O, S, or P, facilitate ion transport by modifying the electronic properties and improving electrolyte wettability. To achieve a balance between capacity, initial coulombic efficiency, and rate performance, the precursor composition, carbonisation temperature, and activation method must be carefully controlled.

3. Lithium Storage Mechanism

Unlike graphite, which stores lithium mainly through a single intercalation mechanism, algae-based hard carbon stores lithium via multiple mechanisms. At higher potentials, lithium adsorption on heteroatom sites, surface defects, and near-surface pores produces a sloping voltage profile. At lower potentials, lithium filling closed or quasi-closed nanopores, along with partial intercalation between enlarged graphene layers within short-range ordered domains, typically gives rise to a low-voltage plateau.

Lithium clusters can be accommodated within nanopores, which significantly increase charge storage without causing large structural expansion. As a result, hard carbon can deliver higher capacities than graphite while

maintaining good mechanical stability. Therefore, the high capacity and complex voltage behaviour of hard carbon anodes, including those derived from algae, arise from the combined effects of lithium adsorption, pore filling, and limited intercalation.

4. Electrochemical Performance

Electrochemical studies show that biomass- and algae-derived hard carbons can deliver reversible capacities above **300 mah g^{-1}** in lithium-ion cells. However, the exact capacity strongly depends on the type of biomass precursor, the carbonisation temperature, and the activation method used. Compared with dense graphite electrodes, the hierarchical porous structure of hard carbon improves electrolyte wettability, reduces lithium-ion diffusion distances, and enables better rate capability and faster charging performance.

The open diffusion pathways and increased interlayer spacing also help mitigate kinetic limitations at low temperatures, leading to better performance under sub-ambient conditions than graphitic anodes. Nevertheless, many of the highest-capacity algae-derived hard carbons have been demonstrated in sodium-ion rather than commercial lithium-ion systems, indicating that further targeted optimization for LIB chemistry is still required.

5. Environmental and Sustainability Advantages

Algal biomass offers substantial sustainability benefits compared with traditional graphite sources. Algae can be cultivated in saline water, wastewater, or photobioreactors on non-arable land, which minimizes competition with food production and enables integrated wastewater treatment and CO_2 capture. Their high areal productivity and short growth cycles permit continuous harvesting and flexible supply chains within biorefinery concepts.

By contrast, natural and synthetic graphite production typically involves mining, chemical purification, and high-temperature graphitization, processes that are energy-intensive and associated with environmental emissions. Substituting part or all of the graphite in LIB anodes with algae-derived hard carbon can therefore reduce reliance on non-renewable resources and align battery technology with broader sustainability goals.

6. Challenges and Limitations

Despite promising properties, algae-based hard carbon faces several obstacles before it can replace graphite at scale. The large surface area and abundance of defects promote extensive solid–electrolyte interphase formation during initial cycling, leading to high irreversible capacity loss and reduced initial coulombic efficiency. In addition, the intrinsically disordered structure generally provides lower electronic conductivity than crystalline graphite, necessitating conductive additives, hybridization with graphitic carbons, or surface coatings.

Parameter	Graphite	Algae-Based Hard Carbon
Structure	Layered, crystalline	Disordered hard carbon, micro/mesoporous
Typical capacity (mah g^{-1})	~ 300–350 in practical LIB anodes	Often ≥300, potentially >400 when optimized
Initial efficiency	High (≥90 %)	Moderate, improved by surface/interface engineering
Rate capability	Moderate	High, due to open pore network and larger spacing
Sustainability	Limited, mining and high-energy processing	High, renewable algal feedstock and CO_2 uptake
Commercial status	Mature, fully commercial	Emerging, mainly at research scale

Material reproducibility and scalability also remain important concerns. Variations in algal species, cultivation conditions, and processing parameters can significantly influence carbon yield, elemental composition, and microstructure, resulting in performance variability. Large-scale adoption will require standardized feedstock preparation, process control, and techno-economic analysis to compare algae-derived hard carbon with established graphite supply chains.

7. Comparison with Graphite Anodes

These comparisons highlight that algae-based hard carbon can surpass graphite in sustainability and rate capability, while matching or exceeding its capacity once materials and interfaces are carefully engineered.

8. Future Research Directions

Future research should emphasize advanced surface engineering to suppress excessive SEI formation and enhance initial coulombic efficiency, for example via pre-lithiation, protective coatings, and optimized electrolyte formulations. Heteroatom doping, controlled graphitization, and integration with more conductive carbons or silicon-based phases could further increase capacity and conductivity. Systematic studies linking algal species, carbonization temperature, activation method, and pore architecture to lithium-storage behavior are needed to establish robust design rules.

On the process side, pilot-scale cultivation and carbonization of algae, coupled with life-cycle assessment and cost analysis, will be essential to evaluate industrial feasibility and environmental benefits relative to graphite. Combining algae-derived hard carbon with other products from algal biorefineries may also improve overall process economics.

9. Conclusion

Algae-based hard carbon is a promising sustainable alternative to graphite for lithium-ion battery anodes. Its disordered structure, hierarchical porosity, and multi-mechanism lithium storage provide the basis for capacities that can exceed those of graphite and support superior rate and low-temperature performance. The use of rapidly renewable algal feedstocks further enhances the environmental profile of next-generation batteries. However, substantial initial capacity loss, modest intrinsic conductivity, and questions surrounding large-scale, reproducible production presently limit industrial deployment. Continued progress in material design, interface optimization, and sustainable process engineering is expected to move algae-derived hard carbon closer to practical implementation as a graphite-replacing anode material in future lithium-ion batteries.

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