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Using algae in Li-ion batteries: A sustainable pathway toward greener energy storage

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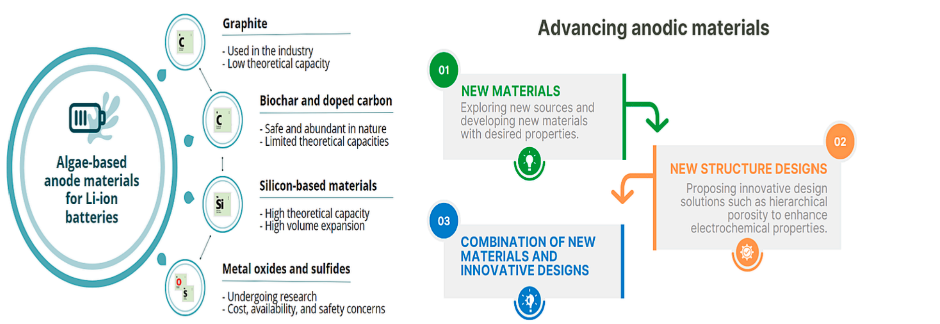
HIGHLIGHTS

- Algae-based materials can serve as biosources and biotemplates for Li-ion batteries.
- Promising materials include carbonaceous materials, biosilica, biopolymers, etc.
- Natural advanced structures have unique properties like hierarchical porosity.
- Applications in all components of the Li-ion battery are discussed.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper reviews and analyzes the innovations and advances in using algae and their derivatives in different parts of Li-ion batteries. Applications in Li-ion battery anodes, electrolytes, binders, and separators were discussed. Algae provides a sustainable feedstock for different materials that can be used in Li-ion batteries, such as carbonaceous material, biosilica, biopolymers, and other materials that have unique micro- and nano-structures that act as biotemplates for composites structure design. Natural materials and biotemplates provided by algae have various advantages, such as electrochemical and thermal stability, porosity that allows higher storage capacity, nontoxicity, and other properties discussed in the paper. Results reveal that despite algae and its derivatives being a promising renewable feedstock for different applications in Li-ion batteries, more research is yet to be performed to evaluate its feasibility of being used in the industry.

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1. Introduction

As the world moves towards a more sustainable and energy-efficient future, lithium-ion (Li-ion) batteries continue to serve as the undisputed champion, powering everything from smartphones to electric vehicles and renewable energy storage systems. The growth of the global market of Li-ion batteries is forecasted to grow steadily and almost exponentially from USD 36.90 billion in 2020 to USD 193.13 billion in 2028 (Fortune Business Insights, 2022). This rapid growth is mainly attributed to the surging demand for electric vehicles and renewable energy storage systems (Lander et al., 2021; Noura et al., 2020; Singh et al., 2023). As a result, there is an urgent need for sustainable, cost-effective, and eco-friendly materials for Li-ion batteries that can meet this industry's high performance and safety requirements.

Lithium-ion (Li-ion) batteries are highly significant across various domains due to their unique properties. They are widely employed in portable electronics like smartphones and laptops because they offer high energy density and lightweight characteristics. In the electric vehicle sector, Li-ion batteries contribute to the growth of clean transportation, while in renewable energy, they play a key role in storing excess energy from sources like solar and wind. Additionally, Li-ion batteries support grid stability, find applications in consumer electronics, power tools, medical devices, and aerospace, showcasing their versatility and adaptability. The significance of Li-ion batteries extends to advancements in technology, sustainability, and the broader transition to cleaner energy solutions. Li-ion batteries consist of two electrodes as the main components separated by an electrolyte and in some cases a physical separator and a binder.

Materials conventionally used in Li-ion batteries include graphitic and carbon-based materials, metal oxides, phosphates, and silicates. Although these materials have shown promising results, they have some limitations and drawbacks. For example, transition metal oxides are limited by cost, availability, and safety concerns (Liang et al., 2013; Wang et al., 2019; Zhao et al., 2016). On the other hand, carbonaceous materials are safer and more abundant. Yet, they have a limited theoretical capacity and lifetime (Li et al., 2021; Roselin et al., 2019; Ye et al., 2021; Yuan et al., 2023) while silicon-based materials have higher capacity but suffer from hazardous volume expansion (Feng et al., 2018; Wu et al., 2019; Zhang et al., 2021). These limitations are driving researchers to develop new materials that will provide environmentally friendly solutions for Li-ion batteries to deliver high energy density and power capability while maintaining long lifecycle and high safety standards (Illa Font et al., 2023; Lv et al., 2019). Examples of biomass based materials that have the potential to be used in rechargeable batteries are lignocellulosic biomass, soybean residue, fruit waste, nutshell, grain waste, etc. (Park et al., 2023).

The use of algae in electrochemical energy storage and generation applications was reviewed elsewhere (Parsimehr and Ehsani, 2020; Torres and De-la-Torre, 2022). Compounds from green algae, such as cellulose and activated carbon, are utilized in creating electrodes and separation membranes for batteries and supercapacitors. Moreover, natural dyes from green algae play a role in developing dye-sensitized solar cells, and microbial fuel cells leverage the oxygen released during algae growth for cathodic reactions, converting H_2 into electricity. Algae have attracted attention as a renewable and environmentally friendly source for various materials used in Li-ion batteries. Algae have many advantages as they are fast-growing, need minimal nutrition and supervision, and can produce different types of bioproducts such as lipids and polysaccharides. Each of these biomaterials can further be processed to obtain an end-product used in Li-ion batteries, such as carbonaceous materials for anodes or alginates for electrolytes.

The choice of algae as a feedstock for energy materials serves more than one goal, as algae can grow in and treat wastewater, capture and use CO_2 emissions, and produce byproducts that can be used for purposes other than Li-ion batteries (Aswathi Mohan et al., 2022; Chen et al., 2022; Dang et al., 2022; Devadas et al., 2021; Kanna Dasan et al., 2023; Kant Bhatia et al., 2022; Kartik et al., 2021; Leong et al., 2022; Nagendranatha Reddy et al., 2019; Pathy et al., 2022; Vo Hoang Nhat et al., 2018; Yu et al., 2017; Zhou et al., 2022). This makes the production process of Li-ion batteries more sustainable and reduces its environmental impact. Algae-derived materials have also shown good performance, stability, and safety for Li-ion batteries (Parsimehr and Ehsani, 2020).

Algae-derived materials have another advantageous characteristic which is their unique detailed morphological structures. These nano- and micro-structures can be used as three-dimensional biotemplates to fabricate innovative structures with enhanced properties such as high surface area. Algal feedstock also contains various dopants and functional groups that provide improved electrochemical properties and more active sites.

However, the utilization of materials derived from algae for different applications in Li-ion batteries did not reach the stage of commercialization yet due to challenges such as scalability, cost and process optimization, and limited understanding of the electrochemistry of algae (Parsimehr and Ehsani, 2020; Torres and De-la-Torre, 2022). This topic is gaining increasing research attention as the demand for high-performance and cost-effective Li-ion batteries with high sustainability and safety standards is growing. The literature contains reviews about advancements in the materials used for Li-ion batteries such as polymer electrolytes (Fan et al., 2021) and anodes (Nzereogu et al., 2022) from different sources including biomass feedstocks (Baskar et al., 2023; Jin et al., 2021; Long et al., 2017). Some reviews discuss the potential of microbe-derived (Wei et al., 2016) and algae-derived (Parsimehr and Ehsani, 2020; Torres and De-la-Torre, 2022) materials in energy generation and storage applications in general. This paper aims to highlight and analyze the latest breakthroughs in utilizing algae for applications in Li-ion batteries specifically. It covers the progress in using materials derived from algae in the anodes, electrolytes, binders, and separators of Li-ion batteries. The novelty of this paper lies in its detailed and specific discussion and comparison between various algae-based materials in each component of the Li-ion battery, in terms of capacity, coulombic efficiency, capacity retention, etc. Results are also presented in tables for each battery component. By highlighting these advancements, this review offers valuable insights into the potential of algae as a sustainable and environmentally friendly feedstock for Li-ion battery applications.

2. Algae-based anodes

The most common standardized commercial anode material for Li-ion batteries is graphite. However, the rising demand for higher energy and power densities, storage capacities, performance rates, and cycling stability calls for more enhanced anode materials. Graphite has a relatively low theoretical capacity (372 mAh/g) and limited rate capability and cycling performance (Xia et al., 2013). Alternatively, silicon (Si) is attracting increasing research attention as it has a theoretical specific capacity that can reach up to 4,212 mAh/g (in the case of $Li_{22}Si_5$) (Zhang et al., 2012). Although ten times higher than graphite, this high specific capacity does not last long because it is impacted by the immense volume change that the Si anodes of Li-ion batteries go through upon lithiation and delithiation (Zhang et al., 2012). Other materials being investigated for Li-ion battery anodes include alloys, metal oxides, and other carbon-based materials (Nzereogu et al., 2022). Fig. 1 presents a visual summary of the anodic materials discussed in this section.

The innovation in the anodes of Li-ion batteries takes two paths, as mentioned in Fig. 1. The first way, as mentioned above, is discovering and developing new materials with desired properties. The second way is proposing new structure design solutions that result in better performance. For example, increasing the surface area by introducing mesopores or large pores increases the capacity, while introducing micropores enhances ion exchange (Baskar et al., 2023; Lu et al., 2017). As will be noticed in this section, studies combine new materials with innovative material designs to tackle the limitations and challenges that

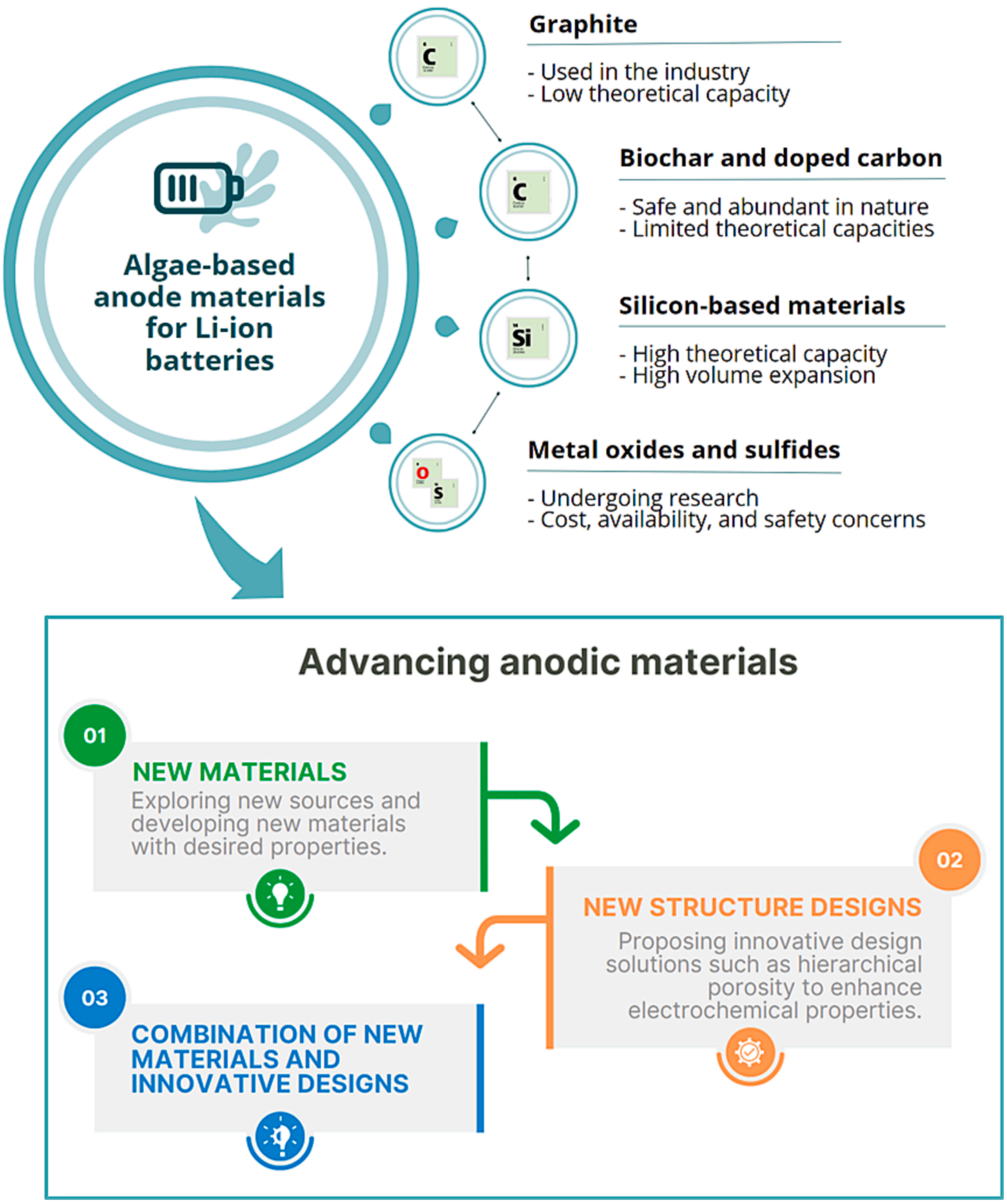

Fig. 1. Visual summary of algae-based anodic materials for Li-ion batteries and development pathways.

the former anode of Li-ion batteries face.

Algae biomass is a sustainable carbon source for the anodes of Li-ion batteries. Like other biomass types, carbon materials are obtained from algae biomass through various carbonization processes such as pyrolysis, gasification, and hydrothermal treatment (Baskar et al., 2023; Jin et al., 2021). The obtained carbon material is typically activated through self-activation or chemical/physical activation to increase its theoretical capacity (Baskar et al., 2023). It can also be doped or modified using oxides, sulfides, and other additives. Algae also serves as a biotemplate to build material designs inspired by nature. Different composites, structures, and processes result in anodes with different properties. This section reviews the experimental work using algae-based sources to fabricate anodes for Li-ion batteries. Table 1 presents a summary of the studies that are discussed in the following subsections. For the sake of comparison, Table 2 presents highlights of electrochemical performance of similar biomass materials from various sources.

2.1. Silica- and silicon-containing anodes

Silicon and silicon-based composites are being investigated as anode materials for Li-ion batteries because of their high capacity (Casimir et al., 2016). Since pure silicon anodes suffer from high volume change and severe capacity loss, it is necessary to couple it with other stable components such as carbonaceous materials. Both silicon-based materials and carbon-based materials can be derived from algae.

Diatoms, a type of algae, are known for their production of high amounts of silica (silicon dioxide, SiO_2) in the form of cell coatings also called frustules. Fig. 2 (A) shows examples of diatoms cell structures. This biosilica can be harvested from aqueous algal biomass or from diatomic fossils found in sediments which are also known as diatomaceous earth (Entwistle et al., 2018; Lisowska-Oleksiak et al., 2014). Nowak et al. (2019) cultivated diatoms (*Pseudostaurosira trainorii*), harvested biosilica from the obtained biomass, and used it to fabricate anodes for Li-ion batteries. Obtaining biosilica was achieved through simple steps that include vacuum filtration and organic matter digestion. This biosilica was combined with carbon black and carboxymethyl

Table 1
Summary of studies on using algae-derived materials in the anodes of Li-ion batteries, sorted according to dates.

Anode material	Year	Source	Synthesis processes	Properties	Ref.	Subsection number
SiO_2/C composite	2021	Silica from diatoms	Pyrolysis	**Delithiation capacities:** ≈800 mAh/g at 50 mA/g and ≈450 mAh/g at 2000 mA/g	(Renman et al., 2021)	2.1
Hydrochar (byproduct of HTL)	2021	algae grown on brackish dairy wastewater	Hydrothermal liquefaction, CO_2 activation, and base-acid wash	**Surface area:** 304.06 m^2/g **Reversible discharge–charge capacity:** 226 and 223 mAh/g at 0.1 A/g after 40 cycles	(Yu et al., 2022)	2.4
Porous carbon SnO_2 nanoparticles	2020	Green algae	Hydrothermal process, carbonization, iron oxide etching	**Surface area:** 798.9 m^2/g **Discharge capacity:** 1235.4 mAh/g at 0.1C after 180 cycles and 416 mAh/g at 1.0C after 250cycles	(Raza et al., 2021)	2.2
Lead adsorbed hydrochar	2020	Algae hydrochar after being used as a lead adsorbent in wastewater	hydrothermal liquefaction, alkali treatment	**Reversible capacity:** 358 mAh/g at 0.1 A/g after 100 cycles **Rate capability:** 383, 312, 261, 214, 175, and 135 mAh/g at 0.1, 0.2, 0.4, 0.8, 1.6, and 3.2 A/g, respectively	(Yu et al., 2021)	2.4
Carbon-MoS_2 composite	2019	Green algae (as a source and a biotemplate)	Hydrothermal process, carbonization	**Discharge capacity:** 300 mAh/g at 5 A/g after 880 cycles	(Seo et al., 2019)	2.5
S-doped carbon aerogel	2019	Carrageenan-Fe hydrogel from red algae	Pyrolysis, carbonization, acid washing	**Surface area:** up to 4037.0 m^2/g **Specific capacitance:** 335F/g (aqueous electrolyte) and 217 F/g (organic electrolyte) at 1 A/g **Maintained capacitance:** 204 F/g at 100 A/g and 173 F/g at 50 A/g in aqueous and organic electrolytes	(Li et al., 2019)	2.3
Carbon MnO/SiOC composite	2019	Green algae (source and biotemplate)	Supercritical CO_2, biosorption, calcination	**Reversible capacity:** 770 mAh/g at 100 mA/g after 200 cycles	(Huang et al., 2019)	2.1 and 2.2
Carbon black + biosilica + sodium carboxymethyl cellulose composite	2019	Biosilica from diatoms	Digestion and acid dissolving to obtain silica	**Specific capacity:** 400 ± 9 mAh/g over 90 cycles	(Nowak et al., 2019)	2.1
N-doped carbon α-Fe_2O_3 composite	2018	Green algae	Spray pyrolysis	**Discharge capacity:** 1281.5 mAh/g at 100 mA/g **Rate performance:** 200-–1000 mA/g **Capacity retention:** 92 % after 100 cycles at 200 mA/g	(Kwon et al., 2019)	2.2 and 2.3
Carbon $ZnMn_2O_4$ composite	2017	Residual microalgae from biofuel industry	Biosorption, hydrothermal treatment, calcination	**Initial discharging capacity:** 1366 mAh/g **Initial charging capacity:** 853 mAh/g **Coulombic efficiency:** 62.4 % **Capacity retention:** 355 mAh/g maintained 10A/g	(Chen et al., 2017)	2.2
Heteroatom doped (S N O) carbon	2017	Carrageenan	Carbonization, activation	**Reversible capacity:** 839 mAh/g at 0.1 A/g after 100 cycles **Capacity retention:** 228 mAh/g maintained at 10 A/g	(Lu et al., 2017)	2.3
Sn/C composite	2017	Microalgal biomass after oil extraction	Carbonization	**Rate capability:** 160.0 mAh/g at 3.5 A/g after 80 cycles **Cycle performance:** 511.7 mAh/g at 200 mA/g after 300 cycles	(Song et al., 2017)	2.2
Carbon Fe_2O_3 composite	2017	Sodium alginate	Calcination	**Reversible capacity:** 703 mAh/g at 100 mA/g after 50 cycles and 384 mAh/g at 2 A/g **Specific capacity:** 1193 mAh/g for the first discharge	(Zhang et al., 2017)	2.2
HCl treated biochar	2017	Green macroalgae	Pyrolysis, HCl treatment	**Specific discharge capacity:** 700 mAh/g at 0.1 A/g	(Salimi et al., 2017)	2.4
MnO/C microtubes	2016	Green algae (spirogyra: spiral tube-like structure)	Biosorption, carbonization	**Reversible capacity:** 610 mAh/g at 200 mA/g after 60 cycles **Rate capability:** 350 mAh/g at 2 A/g	(Wang et al., 2016)	2.2
Porous carbon	2016	Microalgae	Pyrolysis	**Specific capacities:** 445 mAh/g at 0.1C and 370 mAh/g at 1C **Capacity retention:** 95 % after 500 cycles at 1C	(Ru et al., 2016)	2.4
Si–O–C	2016	Microalgae (Nannochloropsis) as source and template	Calcination, supercritical CO_2	**Reversible capacity:** 450 mAh/g at 0.1 A/g over 200 cycles with excellent rate cycling stability and coulombic efficiency (100 %)	(Xia et al., 2016)	2.1
Silicon paper (made of silicon, nanocellulose, and carbon nanotubes)	2015	Nanocellulose from green algae (Cladophora)	Paper making process (sonication, vacuum filtration, drying)	**Areal capacity:** up to 2.5 mAh/cm^2 **Specific capacity (based on Si):** 3200 mAh/g at 200 mA/g.	(Wang et al., 2015)	2.1

(continued on next page)

Table 1 (*continued*)

Anode material	Year	Source	Synthesis processes	Properties	Ref.	Subsection number
Sn/C composite	2014	Green algae (Spirulina) as a source, biotemplate, and biosorbent	Biosorption, calcination	**Specific capacity (based on electrode weight):** 800 mAh/g at 200 mA/g **Discharge capacity:** 520 mAh/g after 100 cycles **Coulombic efficiency:** approx. 100 %	(Tao et al., 2014)	2.2
MnO/C microspheres	2013	Microalgae (Nannochloropsis oculata)	Immersion, calcination	**Reversible capacity:** 700 mAh/g at 0.1 A/g **Cycling stability:** excellent **Capacity retention:** 94 % **Rate performance:** 230 mAh/g at 3 A/g	(Xia et al., 2013)	2.2

Table 2
Examples of non-algae biomass materials and their electrochemical properties.

Biomass source	Properties	Ref.
Cotton	- **Capacity** up to 650 mAh/g at 3C. - **Capacity retention**: 1070 mAh/g after 430 cycles at 0.2C. - **Coulombic efficiency**: 99 %	(Wu et al., 2016)
Bacterial cellulose	- **Capacity** up to 1390 mAh/g at 200 mA/g. - **Capacity retention**: 1135 mAh/g after 200 cycles at 400 mA/g. - **Coulombic efficiency**: 100 %	(Huang et al., 2016)
Rice husk	- **Capacity retention**: discharge capacity increased from 325 mAh/g to 485 mAh/g after 84 cycles.	(Wang et al., 2014)
Corn stalk	- **Capacity** up to 209 mAh/g at 1C. - **Capacity retention**: 203 mAh/g after 200 cycles. - **Coulombic efficiency**: 99.5 %	(Xu et al., 2016a)
Bamboo	- **Capacity retention**: discharge capacity decreased from 586.2 mAh/g at 200 mA/g to 294.7 mAh/g after 180 cycles at 200 mA/g.	(Xu et al., 2016b)
Egg white	- **Capacity** up to 154 mAh/g at 1C. - **Capacity retention**: discharge capacity decreased from 324.2 mAh/g at 0.2C to 189 mAh/g after 10 cycles and 118 mAh/g after 100 cycles at 5C.	(Gao et al., 2016)

cellulose (CMC) to prepare the anode slurry. The porous 3D nanostructures provided by the renewable biosilica act as a buffer to decrease volume expansion and increase the surface area to enhance the storage capacity. The best specific capacity was achieved using a 1:1 biosilica and carbon black ratio, around 409 ± 4 mAh/g at 20 mA/g for 90 cycles. However, at a current density of 500 mA/g, the specific capacity drops to below 100 mAh/g. Similarly, Renman et al. (2021) used biosilica from diatoms to make anode composites for Li-ion batteries. They harvested *Coscinodiscus* from the ocean, purified it, reduced its particle size to a powder form (because regular silica particles have low storage capacity of 200 mAh/g and lower), and finally used glucose to coat the biosilica nanoparticles with carbon through 850 °C pyrolysis. Carbon coating is a method used to overcome the limited electrical conductivity and ion diffusivity of silicon-based anodic materials. The obtained biosilica (75 %wt) was combined with carbon black (10 %wt) and sodium alginate (15 %wt) as a binder. The unique anode composition with a particular activation mechanism resulted in a reversible delithiation capacity up to 800 mAh/g at 50 mA/g. It also demonstrated a capacity up to 150 mAh/g and a specific energy density of around 390 mWh/g when tested in a Li-ion battery.

Xia et al. (2016) and Huang et al. (2019) utilized microalgae as a carbon source and a biotemplate in addition to silicon oxycarbides (Si–O–C) from other sources to fabricate a Li-ion battery anode. The electrochemical performance of Si-O-C composites depends on composition (e.g., Si percentage), amorphicity, and other microstructure properties (Xia et al., 2016). In a study by Xia et al. (2016), microalgae *Nannochloropsis* and tetraethyl orthosilicate were milled, treated with supercritical CO_2, and calcined to obtain a sample of Si–O–C microspheres for Li-ion battery anodes. The low viscosity and high penetration of supercritical CO_2 ensure efficient particle dispersion and mass transfer between microalgae and the Si-containing additive. The proposed structure demonstrated a reversible specific capacity of 450 mAh/g at 0.1 A/g for over 200 cycles due to the increased active surface area made possible by the microalgae biotemplated microstructures. A similar procedure was used by Huang et al. (2019) with Chlorella biomass, after which the treated biomass underwent a biosorption phase to incorporate MnO additives, as shown in Fig. 2 (B). The final C/MnO/SiOC anodic material demonstrated a reversible capacity of 770 mAh/g at 100 mA/g for over 200 cycles.

Nanocellulose from the green algae *Cladophora* was used along with silicon nanoparticles and carbon nanotubes to construct a paper-like anodic structure (Wang et al., 2015). Owing to *Cladophora* nanocellulose physicochemical properties, the Si-based anode sheets showed high flexibility (tensile strength: 27.4 MPa, Young's modulus: 314 MPa, pictures can be viewed in Wang et al. (2015)), lightweightness, and free-standability. They demonstrated a specific electrode capacity up to 800 mAh/g at 200 mA/g, corresponding to a specific capacity of 3200 mAh/g based on the weight of Si only. However, after 100 cycles at 1 A/g, the electrode-specific capacity dropped to 458 mAh/g. The electrodes also had aerial capacities of up to 2.5 mAh/cm^2.

2.2. Metal oxide anodes

2.2.1. Manganese oxide (MnO)

Metal oxides are being investigated thoroughly because of their high reversible capacities. For example, the theoretical capacity of manganese oxide (MnO) is 756 mAh/g which is more than double that of graphite. MnO also has a low operational potential of 1.032 V vs Li/Li$^+$. However, like Si anodes, the high capacity of pure MnO fades rapidly and causes immense volume change. MnO also has low rate capability (Huang et al., 2019; Xia et al., 2013). To address these limitations, studies propose novel anodic composites that combine MnO and carbonaceous or other volume-buffering materials in unique nanostructures.

In a study by Huang et al. (2019), MnO was embedded in the SiOC microspheres through heavy metal biosorption. The addition of MnO was responsible for the reversible capacity while the SiOC was responsible for buffering and accommodating volume change. The electrochemical properties of the fabricated SiOC/MnO microspheres were mentioned in the previous section.

Nannochloropsis oculata biomass was also used to fabricate MnO-based microspheres for Li-ion battery anodes (Xia et al., 2013). The biomass was first purified, then immersed in a $KMnO_4/Na_2SO_4$ solution, after which MnO_2 biosorption occurred. The final microstructures consist of hollow shells made of a carbon matrix, MnO nanoparticles, and hierarchical pores of different sizes. Hierarchical pores facilitate ion transfer and act as an empty space to allow safe volume expansion. This anode composite's reported reversible specific capacity is 700 mAh/g at 0.1 A/g with a capacity retention of 94 %.

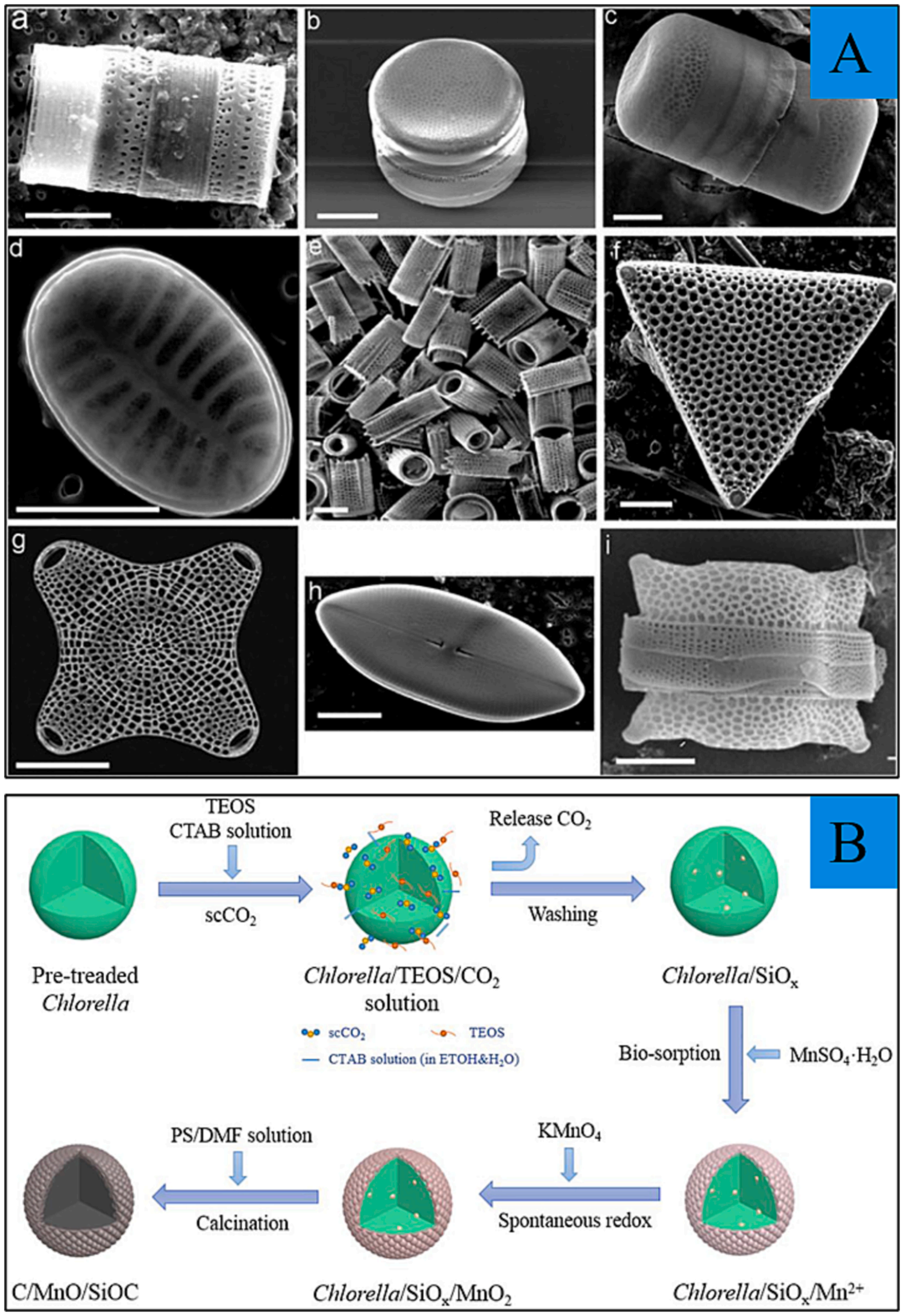

Fig. 2. (A) Silica-containing cell-coatings of diatoms (De Tommasi et al., 2017). (B) Steps of preparing an anodic material made of a C/MnO/SiOC composite (Huang et al., 2019).

Similarly, green algae spirogyra was used as a spiral biotemplate to fabricate MnO-based anode composite (Wang et al., 2016). The green algae were purified, and MnO incorporation was achieved through biosorption and heavy metal deposition. The spiral nature of spirogyra resulted in innovative microtubular carbonaceous structures, as shown in Fig. 3. A reversible specific capacity of 610 mAh/g at 200 mA/g was achieved and maintained for 60 cycles.

A more environmentally friendly method is using the residues of microalgae biomass after biofuel production to fabricate anodic materials. Chen et al. (2017) utilized residual microalgae which contains broken microalgae cells as a carbon source and a biotemplate that provides spherical porous architectures to combine carbon with $ZnMn_2O_4$. The carbon/$ZnMn_2O_4$ composite was prepared through hydrothermal treatment and delivered a capacity of 355 mAh/g at 10 A/g and a high capacity of 1450 mAh/g at 0.2 A/g after 150 cycles.

2.2.2. *Tin and tin oxide (SnO)*

Tin and tin oxide are also being investigated as potential anode materials for Li-ion batteries due to their high capacity (e.g., 993 mAh/g for $Li_{4.4}Sn$), abundance, relative safety, and low environmental impact. However, like many other high-capacity materials, tin-based anodic materials suffer from high volume change during lithiation and delithiation. To address this issue, Raza et al. (2021) fabricated a mesoporous architecture of a SnO_2-carbon composite with an increased surface area of 798.9 m^2/g due to the high porosity. The composite was prepared by carbonizing microalgal biomass mixed with Sn- and Fe-containing solutions then etching Fe to leave behind mesopores in the carbonaceous matrix. Fig. 4 illustrates the explained process. The

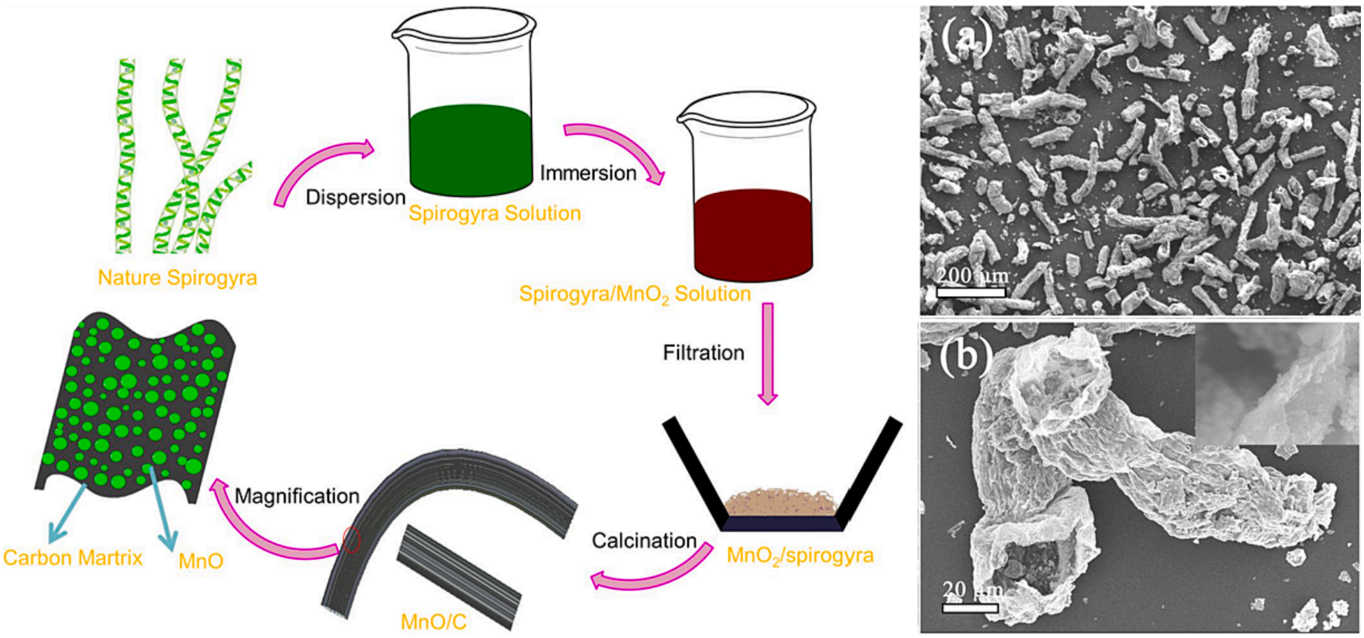

Fig. 3. Illustration of algae/MnO composite preparation and SEM images of the sample (Wang et al., 2016).

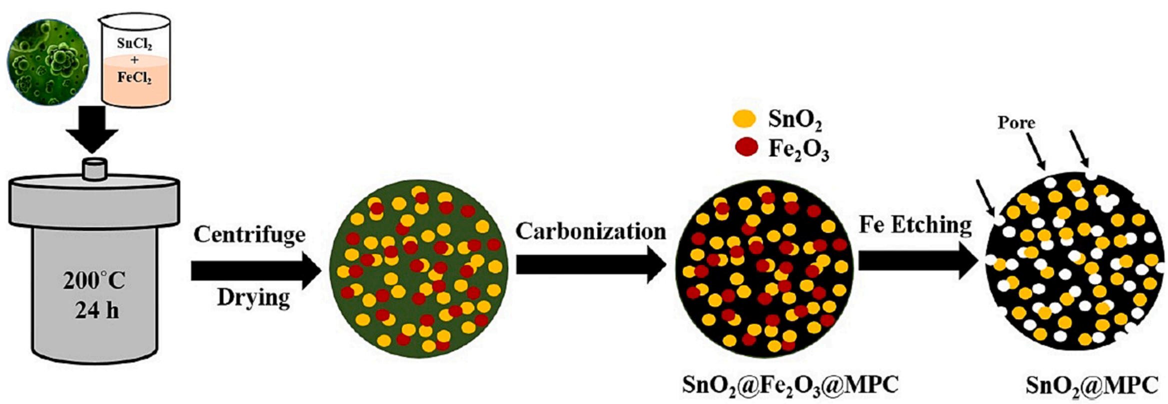

Fig. 4. Process of fabricating mesoporous Sn- and Fe-based anodic composite by (Raza et al., 2021).

discharge capacity of this anodic nanocomposite was 1235.4 mAh/g at 0.1C after 180cycles and 416 mAh/g at 1.0C after 250cycles.

Tao et al. (2014) used *Spirulina platensis* to fabricate an Sn-based carbonaceous composite for the anode of Li-ion batteries. They used microalgae as a source of carbonaceous materials, a biotemplate for the structure of the composite, and a biosorbent for the additives. The composite was made by biosorbent of Sn particles onto the microalgae, calcination of the composite, and finally coating with polystyrene (PS) to ensure that the Sn particles (20–30 nm) stay well anchored to the microalgae and uniformly distributed. The discharge capacity of this composite is 520 mAh/g after 100 cycles, with high cycle stability and coulombic efficiency.

Since using residual microalgal biomass after oil extraction is more feasible than using new biomass, Song et al. (2017) valorized the biomass residues of *Chlorella* sp. after oil extraction to make a novel Sn-based anodic composite. The composites also contained N- and P-doped carbon obtained from the biomass. Additionally, they used a biomass that has not undergone an oil extraction process and found that when the lipids are removed, the material's electrochemical properties (e.g., rate capability and improved cycle performance) were enhanced.

2.2.3. Iron oxide (FeO)

Other types of oxides that are being studied as candidates for the anodes of Li-ion batteries are iron oxides. They have a high theoretical capacity (e.g., 1007 mAh/g for Fe_2O_3), are abundant in nature, and have relatively high corrosion resistance. Iron oxides suffer from the same limitations of other oxide composites such as volume expansion and low conductivity (Kwon et al., 2019; Zhang et al., 2017). Fe_2O_3 is often coupled with a carbonaceous host material to address its limited electrical conductivity. Carbonaceous materials from algae cannot only be obtained from full biomass and deoiled biomass, but also from algae derivatives such as alginates. For example, Zhang et al. (2017) fabricated an anode material made of iron alginate through spray pyrolysis and subsequent calcination of sodium alginate and an iron-containing solution, as shown in F. The mesoporous Fe_2O_3/C anode composite delivered a reversible capacity of 703 mAh/g at 100 mA/g after 50 cycles and 384 at 2 A/g.

Spray pyrolysis was also used by Kwon et al. (2019) to prepare an iron oxide carbonaceous active material for Li-ion batteries. In their work, green algae were used as a carbon source and a biotemplate. The final anode material consists of 70 % active material, 20 % carbon black, and 10 % carboxymethyl cellulose. It demonstrated improved conductivity and reduced volume expansion, which resulted in capacity retention of 92 % after 100 cycles at 200 mA/g, a discharge capacity of 1281.5 mAh/g at 100 mA/g, and a good rate performance window between 200 mAh/g and 1000 mAh/g. While the testing and study of metal oxides with algae are currently limited, there is a need to explore additional composites.

2.3. Biochar, porous carbon, and doped carbon

Algal biomass is a sustainable source of carbonaceous materials that can be used in the anodes of Li-ion batteries. Hydrochar is a carbonaceous material commonly obtained from algal biomass through hydrothermal liquefaction (HTL) (Elliott et al., 2015; Leong and Chang, 2023; Yu et al., 2017). The process of hydrothermal liquefaction produces biofuel, and 20 %-40 % of the output as a byproduct in the form of hydrochar that can be valorized for Li-ion batteries applications (Yu et al., 2022). Yu et al. (2021) proposed a double valorization technique in which they first used the hydrochar from algal biomass as a lead adsorbent, then as a carbonaceous anode material. They obtained the hydrochar through hydrothermal liquefaction and applied an alkali post-treatment step to enhance the electrochemical properties of the final lead-adsorbed carbonaceous anode material. The final product delivered a reversible capacity of 358 mAh/g at 0.1 A/g after 100 cycles with good rate capability. Yu et al. (2022) also valorized hydrochar from the hydrothermal liquefaction of algae cultivated in brackish water. Their method has triple advantages as it treats wastewater, produces carbon–neutral biofuel, and produces carbonaceous materials for battery anodes. To obtain the anode material, the algae biomass goes through lipid extraction, CO_2 activation, and finally purification from metals and SiO_2 (interestingly, SiO_2 and other metals proved positive results as potential anode materials in other studies (Renman et al., 2021; Nowak et al., 2019; Xia et al., 2016; Wang et al., 2015)). The reversible discharge capacity of the fabricated hydrochar anode material was 226–223 mAh/g at 0.1 A/g after 40 cycles with a high coulombic efficiency of 98.7 %. The anode material also had a surface area of 304.06 m^2/g (Yu et al., 2022).

Porous carbon can also be obtained from algae through simple pyrolysis (pyrolytic carbon) (Ayub et al., 2022; Leong and Chang, 2023; Sun et al., 2022). Ru et al. (2016) used microalgae to obtain pyrolytic carbon with hierarchical porosity and graphitic structure. The anode material demonstrated a capacity of 445 mAh/g at 0.1C and 370 mAh/g at 1C. After 500 cycles, the sample maintained a capacity retention of 95 % at 1C. Similarly, Salimi et al. (2017) used *Cladophora glomerata*, a green alga, to obtain pyrolytic algae for the anode of Li-ion batteries. Their results suggest that HCl-treated biochar has better electrochemical properties than nontreated biochar. Their sample comprises 75 % HCl treated biochar, 15 % carbon black, and 10 % PVDF. It demonstrated high active surface area, high thermal stability, and a discharge capacity of 700 mAh/g at 0.1 A/g.

Carbon doping is another method to improve carbonaceous anode materials' electrochemical properties. Doped carbon can be combined with other additives such as Fe_2O_3 (Kwon et al., 2019) or used alone as the active anode material (Li et al., 2019; Lu et al., 2017). Nitrogen is a good dopant for carbonaceous Li-ion battery anode materials because it is more electronegative than carbon, it introduces more defects and active sites, which lead to improved capacity and Li-ion transport (Kwon et al., 2019). In addition to nitrogen, doping can be done using other elements, such as sulfur and oxygen.

Synthetic doping through post-treatment typically yields unstable anodic materials and is costly. Therefore, using renewable materials such as algae presents an attractive alternative, as the algal biomass and its derivatives contain both carbon and its dopants. Lu et al. (2017) investigated the fabrication of anode material for Li-ion batteries made of carbon doped with heteroatoms. They used the algae-derived sulfur-rich carrageenan as a renewable source of the doped carbonaceous material. In addition to sulfur, carrageenan contains other components that allow nitrogen and oxygen doping. The heteroatom doped anode material was prepared through simultaneous carbonization and activation. It resulted in an aerogel with a surface area of 852–925 m^2/g, a capacity of 839 mAh/g after 100 cycles at 0.1 A/g for Li-ion battery and 228 mAh/g at 10 A/g, and a relatively low coulombic efficiency of 62 %. The high sulfur content of carrageenan also makes it a suitable source for anode materials of Li-S batteries, as studied by Li et al. (2019) in which they used carrageenan via a similar process to fabricate an anode material for Li-S battery with a high aerogel surface area of 4037.0 m^3/g.

2.4. Molybdenum sulfides (MoS_2)

Sulfides are also being investigated for application in the anodes of Li-ion batteries. For example, MoS_2 has high capacity (~1400 mAh/g) and is distinguished by its excellent cycle performance, demonstrating good rate capability and capacity retention (Seo et al., 2019). However, since MoS_2 is not a good conductor, it is often combined with conductive materials such as carbon. For example, Seo et al. (2019) used green microalgae as a carbon source and a structure biotemplate to fabricate a novel carbon-MoS_2 anode composite for Li-ion batteries. Fig. 5 shows details of the mentioned composite. The deoiled microalgae maintained its spherical structure and provided a hollow 3D microstructure with increased internal active sites for enhanced electrochemical properties. Carbon from microalgae also contains natural nitrogen doping, further increasing the number of active sites, thus improving capacity and ion transport. The proposed carbon-MoS_2 composite achieved a 300 mAh/g capacity at 5 A/g after 880 cycles, demonstrating excellent cycle stability.

3. Algae-based electrolytes

The most important properties of electrolytes in Li-ion batteries, in particular, are conductivity towards lithium ions, safety indicated by thermal and conduction stability, transparency, and environmental friendliness. Solid/quasi-solid polymer electrolytes are more thermally and electrochemically stable than regular liquid electrolytes which are prone to leakage. Many solid electrolytes have shown favorable ionic conductivities, activation energies, and thermal and electrochemical stabilities (Temeche and Laine, 2022).

Algae naturally produce various types of polymers suitable for the fabrication of electrolytes. Typically, polymers such as carrageenan are used as a host material, and lithium salts are used as dopants or additives to enhance the electrolyte's conductivity. Studies have explored the use of carrageenan, agar-agar, chitosan, and alginate to fabricate polymer electrolytes for Li-ion batteries, all of which are biopolymers that can be extracted from the renewable feedstock of algae. Table 3 shows a summary of those studies.

Carrageenans are a family of polysaccharide biopolymers that are widely used in the food and cosmetics industries, mainly as gelling and thickening agents. Increasing attention is also being given to carrageenans (esp. *iota* carrageenan) for the fabrication of electrolytes. Carrageenan derivatives can also be modified and functionalized to achieve enhanced properties. For example, Mobarak et al. (2015) investigated the use of *kappa-* and *iota-* carboxymethyl carrageenan for the fabrication of solid polymer electrolytes. The films are prepared through a solution casting technique and consist of either *kappa-* or *iota-*carboxymethyl carrageenan in combination with lithium nitrate ($LiNO_3$) as the salt that facilitates ion transfer and acetic acid as the solvent. Both samples showed high ionic conductivities, with the *kappa-* based sample having a slightly higher conductivity of 5.51×10^{-3} S/cm compared to 5.85×10^{-3} S/cm of the *iota-* based sample. The samples demonstrated electrochemical stability up to ~3.0 V and activation energies of 0.18 and 0.38 eV for *kappa-* and *iota-*carboxymethyl carrageenan, respectively.

The same salt ($LiNO_3$) was also used with alginate as the host polymer and demonstrated ionic conductivity of 1.14×10^{-4} S/cm (Fuzlin et al., 2020). Alginate is an attractive polymer that can be extracted from

Fig. 5. Details of the carbon-MoS_2 anode composite by (Seo et al., 2019).

Table 3
Summary of electrolytes made of algae-derived materials.

Electrolyte polymer	Salt	Ionic conductivity @ambient T	Year	Ref.
Carboxymethyl carrageenan	Lithium nitrate ($LiNO_3$) salts	<5.51×10^{-3} S/cm	2015	(Mobarak et al., 2015)
Carrageenan	Lithium chloride (LiCl)	<5.33×10^{-3} S/cm	2018	(Chitra et al., 2019)
Carrageenan	Lithium perchlorate $LiClO_4$	3.33×10^{-3} S/cm	2019	(Chitra et al., 2020a)
Carrageenan	Lithium trifluoromethanesulfonate ($LiCF_3SO_3$)	1.27×10^{-3} S/cm	2019	(Chitra et al., 2020b)
Alginate	Lithium nitrate ($LiNO_3$)	1.14×10^{-4} S/cm	2019	(Fuzlin et al., 2020)
Agar-agar	Lithium chloride (LiCl)	$3.12 \pm 0.11 \times 10^{-2}$ S/cm	2022	(Hazaana et al., 2023)
Agar-agar	NH_4SCN salts	1.03×10^{-3} S/cm	2016	(Selvalakshmi et al., 2017)
Agar-agar and chitosan	Lithium perchlorate ($LiClO_4$)	4.56×10^{-4} S/cm	2021	(Hazaana et al., 2023)

algae and has favorable properties such as nontoxicity, mechanical strength, and biocompatibility.

Other studies investigated the use of *iota*-carrageenan with various lithium salts such as LiCl (Chitra et al., 2019), $LiClO_4$ (Chitra et al., 2020a), and $LiCF_3SO_3$ (Chitra et al., 2020b) as electrolyte components for Li-ion batteries. These salts in combination with *iota*-carrageenan and water as the solvent demonstrated ionic conductivities of 5.33×10^{-3} S/cm, 3.57×10^{-4} S/cm, and 1.27×10^{-3} S/cm, respectively. The free-standing films containing $LiCF_3SO_3$ also showed good electrochemical stability up to 3.52 V. Additionally, Chitra et al. (2020a) found that using a plasticizer (Succinonitrile, SN) in the electrolyte increases the ionic conductivity from 3.57×10^{-4} S/cm to 3.33×10^{-3} S/cm, shows good electrochemical stability up to 3.1 V, results in a low activation energy of 0.10 eV and better flexibility.

Agar-agar is another polysaccharide polymer that can be extracted from algae and is investigated as a potential electrolyte material for Li-ion batteries. Hazaana et al. (2023) were able to obtain an exceptionally high ionic conductivity of $3.12 \pm 0.11 \times 10^{-2}$ S/cm using an electrolyte made of agar-agar and LiCl. Their sample showed high amorphousness, low glass transition temperature, and reversibility indicated by the enhanced cycle performance. Selvalakshmi et al. (2017) used agar-agar with a different dopant (NH_4SCN) and obtained an ionic conductivity of 1.03×10^{-3} S/cm and a low activation energy of 0.25 eV.

In another study, agar-agar was used with chitosan polysaccharide polymer. In their study, Leo Edward et al. (2022) used chitosan extracted from shrimp shells. Interestingly, chitosan can also be extracted from algae. Leo Edward et al. (2022) fabricated an electrolyte made of agar-agar, chitosan, polyethylene glycol (PEG) as a plasticizer, and lithium perchlorate ($LiClO_4$) as a doping lithium salt. The sample demonstrated an amorphous structure, high elongation behavior, an ionic conductivity of 4.56×10^{-4} S/cm, and good electrochemical stability up to 3.3 V.

The discussed studies suggest that algal feedstock can be used to produce polymers for solid polymer electrolytes with lithium salts for Li-ion batteries.

4. Algae-based binders

Binders are used to hold the electrode components (e.g., active material and additives) together, stick them to the current collector, and allow better contact between the electrodes and the electrolyte. Currently, the typical material used in binders of Li-ion batteries is polyvinylidene fluoride (PVDF). Although this material is commercially acceptable, it poses safety threats. It is highly flammable, toxic, mutagen, and tumorigenic, and can cause hazardous thermal runways (García et al., 2018). One solution to address these risks is to treat the binder materials at the end of their life and reuse them in new batteries. Another solution is to develop new materials that are safer and more environmentally friendly.

Many biobased materials are being investigated for their applicability as binders in Li-ion batteries, such as alginate, carboxymethyl cellulose (CMC), xanthan gum, guar gum, karaya gum, gum Arabic, agarose, carrageenan, etc. (Bie et al., 2017; Cuesta et al., 2015; Hwang et al., 2016; Jeong et al., 2015; Kovalenko et al., 2011; Ling et al., 2015; Liu et al., 2015, 2005). Among the materials that can be extracted from algae, alginate, CMC, and carrageenan have shown the potential to serve as binder materials for Li-ion batteries. Table 4 summarizes the studies available on these materials.

Alginate is water soluble, can be used in cathodes and anodes, can be crosslinked using different dopants such as Al and Ba, and has shown improved electrochemical performance, as discussed below. Similarly, CMC is water soluble, cheap, and environmentally friendly.

Rheological properties such as viscosity play an important role in selecting the suitable binder. García et al. (2018) studied the use of alginate and CMC binders in the anodes of Li-ion batteries. The active material of the used anodes was graphite, and the conductive additive was carbon black. Their results demonstrated that the alginate slurries are more viscous than their CMC counterparts. For example, at a concentration of 1.5 % and a shear rate of 50 s^{-1}, alginate had a viscosity of 1.26 Pa·s while CMC had 0.20 Pa·s. Cuesta et al. (2015) also investigated the use of alginate, CMC, and carrageenan among other polymers in graphite anodes of Li-ion batteries. Alginate and CMC showed excellent thermal and electrochemical stability and electrochemical performance similar to PVDF. They maintained cycling efficiencies up to 97 % and capacity retention up to 90 %. On the other hand, carrageenan showed poor performance.

In addition to graphite, alginate is suitable for silicon anodes because it contains carboxyl groups that induce stability by forming bonds with

Table 4
Summary of binders made of algae-derived materials.

Binder polymer	Electrode material	Viscosity	Capacity retention	Other properties	Year	Ref.
Sodium alginate (SA)	dilithium terephthalate	–	0.06 % capacity decay per cycle	- **Capacity:** 200 mAh/g at 0.1C after 100 cycles - **Coulombic efficiency:** ~100 %	2019	(Zhang et al., 2019)
SA, CMC	Graphite	SA: 1.26 Pa·s CMC: 0.20 Pa·s	–		2018	(García et al., 2018)
SA	Mn-based oxides (cathode)	–	Ba-doped: 82.5 % Al-doped: 99.9 %	- **Voltage decay:** 0.326 V (Ba-doped) and 0.208 V (Al-doped) after 150 cycles	2018	(Zhang et al., 2018)
SA	Silicon	Up to 30270 mPa·s	49.1 % after 200 cycles at 840 mA/g (Ba-doped)	- **Capacities:** up to 2100 mAh/g after 300 cycles at 420 mA/g	2017	(Wu et al., 2017)
CMC, SA, carrageenan, and others	Graphite	–	>90 %	- **Cycle efficiencies:** >97 % - **Discharge capacities:** 190 mAh/g (SA)	2015	(Cuesta et al., 2015)
Alginate and CMC	$LiNi_1/3Mn_1/_3Co_1/_3O_2$ (NMC) - (cathode)	–	90.1 % (CMC) and 89.2 % (alginate) after 200 cycles	- **Discharge capacities:** 141.9 mAh/g (CMC) and 126 mAh/g (alginate) after 200 cycles at 0.5C - **Activation energies:** 27.4 kJ/mol (CMC) and 33.7 kJ/mol (Alginate)	2013	(Xu et al., 2013)
Alginate	Silicon	Varies depending on concentration	Stable performance up to 100 cycles at 4200 mA/g	- **Capacity:** <2000 mAh/g at 4200 mA/g	2011	(Kovalenko et al., 2011)

silicon. Various alginate binders were prepared by Wu et al. (2017) using different crosslinkers. Alginates crosslinked with Al and Ba showed the best results with capacities around 2100 mAh/g after 300 cycles at 420 mA/g. The Ba-crosslinked alginate binder also showed a high viscosity of 30270 mPa·s, a capacity retention of 49.1 % after 200 cycles at 840 mA/g, and good adherence to the current collector. Additionally, the use of alginate as a binder in the silicon anodes of high-capacity Li-ion batteries has shown enhanced cycle stability at 4200 mA/g with capacities up to 2000 mAh/g, with a lower cost and environmental impact compared to PVDF binders (Kovalenko et al., 2011).

Al- and Ba-doped alginate binders also suit manganese-based oxide cathodes in Li-ion batteries (Zhang et al., 2018). They stabilize the electrode resulting in reduced capacity loss and voltage fading. The fabricated alginate binders achieved capacity retention of 82.5 % (Ba-doped) and 99.9 % (Al-doped), and slight voltage decays of 0.236 V (Ba-doped) and 0.208 V (Al-doped) after 150 cycles (Zhang et al., 2018). CMC was also investigated in a manganese-containing cathode and compared with alginate and PVDF binders (Xu et al., 2013). It demonstrated the best rate capability, cycling performance, and charge transfer, while alginate and PVDF delivered better discharge capacity.

Electrodes made of other organic materials, such as dilithium terephthalate anodes also showed improved performance when bound with alginate as compared to the conventional PVDF binder (Zhang et al., 2019). Combining the water-soluble dilithium terephthalate and alginate enhances ion and electron transfer resulting in better electrochemical properties. Zhang et al. (2019) used a sodium alginate binder in dilithium battery. They achieved a capacity of 200 mAh/g at 0.1C after 100 cycles with a low capacity decay of 0.06 % per cycle, a stable cycling performance up to 1000 cycles, and a coulombic efficiency of ~100 %.

5. Algae-based separators

Physical separators or membranes highly impact the properties of Li-ion batteries. They serve as a barrier that hinders intermixing between the anode and cathode while being porous enough to allow Li-ion transport. It governs properties such as battery capacity, cycling stability, safety, and thermal stability. The efficiency, functionality, and feasibility of a material to be used as a battery separator are determined by its mechanical strength, thickness, porosity, electrolyte wettability, electrochemical and thermal stability, and environmental stability. Commercial separators which are made of polyolefins (e.g., PP: polypropylene and PE: polyethylene) have good mechanical properties and electrochemical stability. Still, their limitation lies in their low thermal stability and wettability (Tan et al., 2020).

Alginate and cellulose are two biomaterials that can be extracted from algae and used as environmentally friendly renewable alternatives in Li-ion battery separators. Since alginate is hydrophilic, it allows good electrolyte absorption and is thermally stable. On the other hand, cellulose has favorable electrochemical and mechanical properties (Tan et al., 2020). Table 5 summarizes the studies that were performed using materials that can be extracted from algae to make separators for Li-ion batteries.

Tan et al. (2020) combined calcium alginate and cellulose through a paper-making process to make a Li-ion battery separator with good thermal and electrochemical properties. The integration of cellulose into the large alginate fibers resulted in a dense structure that showed no thermal shrinkage up to 120 °C, wettability of 257 %, capacity retention of 90 % after 100 cycles, and coulombic efficiency of around 99 %. Wen et al. (2017) also used alginate to fabricate a separator with high thermal stability (up to 150 °C) for high-voltage Li batteries. Their sample also showed improved cycle performance compared to the commercial PP separator, demonstrated by 79.6 % capacity retention after 200 cycles at 55 °C for the alginate separator and 69.3 % for the PP separator at the same conditions.

Alginate can also be combined with PP or other additives to enhance the separator's properties. For example, Wang et al. (2023) used sodium alginate to fabricate a novel separator material in combination with PP nonwoven fabric and halloysite nanotubes. The hollow and porous structure improves ion transfer and electrolyte wettability while maintaining minimal thermal shrinkage of up to 1–4 % at 200 °C for 30 min and excellent electrochemical properties such as 99.1 % capacity retention and other properties mentioned in Table 5. Song et al. (2019) used sodium alginate with another additive called attapulgite (ATP) which has a porous structure and can maintain its stability up to 800 °C (Frost and Ding, 2003). The degradable yet thermally stable and fire-retardant composite showed excellent electrolyte uptake of 420 % and capacity retention of 82 % after 700 cycles. Overall, alginate and cellulose, whether alone or in composites, have shown the potential to be used to fabricate Li-ion separators.

6. Research needs and future direction

This review summarizes and analyzes the potential of algae as a sustainable feedstock for producing different Li-ion battery components such as anodes, electrolytes, binders, and separators. Fig. 6 presents a visual summary of the aspects discussed in this paper. Algae biomass can either be used as a whole in the production process, or only selectively extracted biomaterials such as alginate are used. Using full biomass is more cost-efficient because no purification or separation pretreatment

Table 5
Summary of separators made of algae-derived materials.

Algae-based material	Additives	Wettability	Thermal stability	Electrochemical stability	Year	Ref.
Sodium alginate (SA)	Halloysite nanotubes, propylene nonwoven fabric (PP), N-methyl pyrrolidone (NMP)	- **Electrolyte uptake:** 150.9 %	Minimal thermal shrinkage of 1–4 % at 200 °C for 30 mins	- **Capacity retention:** 99.1 % - **Discharge capacity:** 159.2 mAh/g at 0.2C after 100 cycles - **Coulombic efficiency:** ~100 %	2023	(Wang et al., 2023)
Calcium alginate, cellulose	–	- **Electrolyte uptake:** 257 %	No melting or shrinkage at 120 °C	- **Capacity retention:** 90 % after 100 cycles - **Discharge capacity:** 160 mAh/g at 0.5C after 100 cycles - **Coulombic efficiency:** ~99 %	2022	(Tan et al., 2020)
Sodium alginate (SA)	Attapulgite (ATP)	- **Electrolyte uptake:** 420 %	Almost no shrinkage at 250 °C for 2 h	- **Capacity retention:** 82 % after 700 cycles - **Rate capability:** 115 mAh/g at 5C	2019	(Song et al., 2019)
Alginate	–	–	Thermally stable up to 150 °C	- **Capacity retention:** 79.6 % after 200 cycles at 55 °C - **Discharge capacity:** 117 mAh/g after 200 cycles.	2017	(Wen et al., 2017)

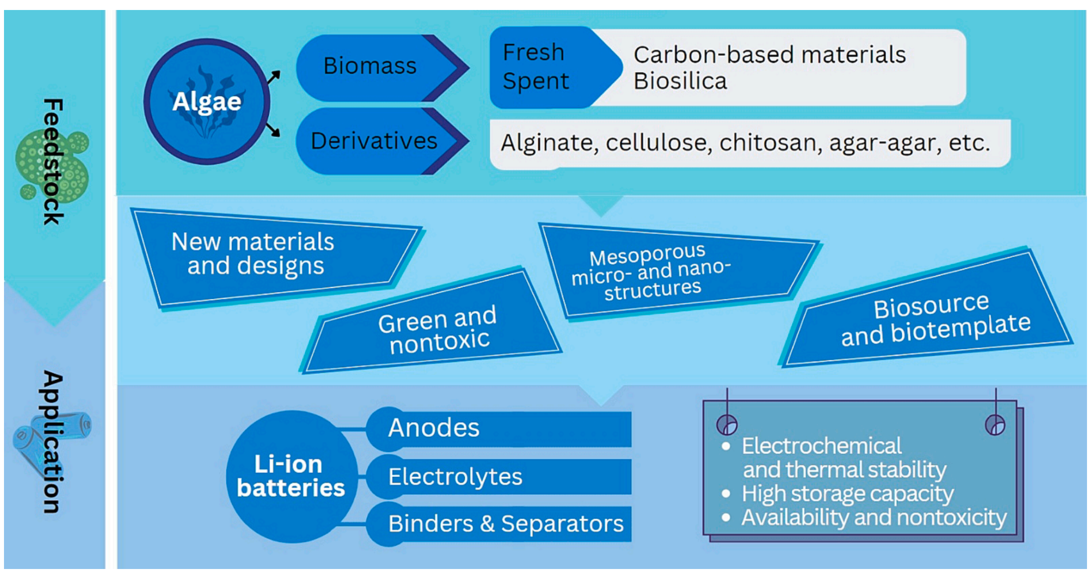

Fig. 6. Visual summary of the aspects discussed in this paper.

steps are required. It is also more feasible to use algal biomass that has been used for other purposes previously, such as biofuel production or wastewater treatment. As discussed in this review, algal biomass that has undergone lipid extraction illustrated better electrochemical properties because of lower oil content. Similarly, algal biomass used as an adsorbent also showed enhanced properties. On the other hand, using specifically extracted biomaterials such as alginate is more suitable for battery components that require high purity, such as electrolytes.

Algae and algae-based materials have proven that they can be used in Li-ion batteries to address various limitations of the conventional materials, such as limited storage capacity (i.e., graphite theoretical capacity), cycling performance, safety concerns (e.g., volume expansion, toxic solvents, etc.), and environmental hazards. There are two approaches to address these challenges:

Exploring new materials.
Developing innovative structures using conventional materials.

This paper discussed the contribution of algae and algae-derived materials to the two pathways. In many cases, the two approaches were used together to exploit the highest benefits that the algal feedstock can offer. The use of algae as a material source and a biotemplate is attractive and promising as their morphological 3D microstructures have hierarchical porosity and high surface area while being stable because they are built by nature. For example, anodic graphite can be replaced by carbonaceous materials from algae that have high surface area, active sites, and thus storage capacity. Carbon and biochar from algae are also naturally doped, being more stable than synthetically doped carbons. The doping percentage can be modified and tailored to achieve the desired percentage by controlling the growth factors that the algae are exposed to in their early phases. Still, limited information is available on this point. Further research, utilizing various compositions of culture media, is required to thoroughly study and analyze the impact of growth factors on the doping percentage and composition of the final product. Other anode composites discussed in this paper include metal oxides, sulfides, and silica. Since silica is a major constituent of diatoms, it is an attractive renewable material for silicon anodes. Its morphology also gives it high buffering space to accommodate volume change while maintaining its natural stability. Another solution to tackle the issue of hazardous volume expansion is coating microstructures as discussed in previous sections.

Addressing the research needs for algae-based anodes involves a multifaceted approach. To overcome the challenge of limited storage capacity, researchers should thoroughly explore growth conditions, fine-tune culture media compositions, and investigate genetic engineering or selective breeding of algae strains. Advanced characterization techniques are crucial to analyze the underlying mechanisms influencing storage capacity. Concurrently, mitigating volume expansion during charge and discharge cycles demands innovative coating technologies, nanostructuring, and a deep understanding of electrolyte influences. Mechanical properties under various cycling conditions need comprehensive studies to identify failure mechanisms and enhance durability. Scaling up production necessitates optimizing cultivation techniques, developing cost-effective large-scale cultivation methods, and investigating efficient harvesting and processing techniques.

In electrolytes, polymer electrolytes are safer because they do not face the leakage problem like liquid electrolytes do. Polymers from algae such as carrageenan, agar-agar, chitosan, and alginate are being explored as candidate biomaterials for the electrolytes of Li-ion batteries and have shown promising results. When mixed with lithium salts, excellent cycle performance, safety, and conductivities up to $3.12 \pm 0.11 \times 10^{-2}$ S/cm. Combinations of different lithium salts and algae-derived polymers should be investigated in the future to achieve the best results. Similarly, algae-derived polymers are a safer and more sustainable alternative to the conventional binders and separators of Li-ion batteries. The water-soluble alginate, cellulose, and carrageenan have shown the potential to replace PVDF binders requiring toxic solvents. They have good viscosities, are more electrochemically stable, and allow better ion transport. However, parameters (e.g., concentration, crosslinking agents, etc.) of these polymers should be optimized as small changes highly impact the final properties. Since alginate and cellulose are hydrophilic, they can also replace polyolefins which are the conventional separator materials and provide higher wettability, stability, and capacity retention (e.g., 79.6 % for alginate vs 69.3 % for PP, and 99.1 % for a combination of the two). Other algae-derived polymers are yet to be explored. Investigating the utilization of sustainable materials simultaneously in multiple components of the Li-ion battery is also recommended. Future studies should also focus on optimizing the best results for scaleup, feasibility analysis, and life cycle assessments.

Regarding electrolytes, a paramount focus should be placed on achieving and sustaining high ionic conductivity across diverse algae-derived polymers and lithium salts. Compatibility issues with different electrode materials, as well as stability under varying operating conditions, including temperature and voltage, necessitate thorough investigation. Moreover, the challenge of obtaining high-purity algae-derived polymers for specific applications requires advanced extraction techniques and purification processes. Regarding binders, optimization of crucial parameters such as concentration, crosslinking agents, and composition is imperative, considering their significant impact on final properties. Ensuring material compatibility with diverse electrode materials and maintaining stability throughout the battery's lifespan are critical considerations. The scalability of binder production from lab-scale to industrial-scale introduces challenges related to cost-effectiveness and consistent quality. Moving on to separators, addressing the mechanical strength requirement is essential to withstand the operational demands of batteries. Achieving and sustaining high wettability with the electrolyte is crucial for efficient ion transport, demanding further research and development. Ensuring environmental stability under diverse conditions, including exposure to various electrolytes, temperatures, and humidity levels, requires comprehensive studies for the successful integration of algae-based separators into Li-ion batteries.

7. Conclusions

The paper reviews sustainable algal feedstock for Li-ion batteries, exploring studies using algae, composites, or algae-derived materials for anodes, electrolytes, binders, and separators. Investigations into biochar, silica, and composites aim to enhance storage capacity. Algal polymers (alginate, carrageenan, cellulose, chitosan, agar-agar) show promise for electrolytes, binders, and separators due to stability, wettability, ion conductivity, and sustainability. Challenges include limited storage and volume expansion, addressed through new materials with higher surface area. Further research and testing are essential for scalable industrial application.

CRediT authorship contribution statement

Soumaya Grira: Writing – original draft. **Mohammad Alkhedher:** Supervision, Writing – review & editing. **Hadil Abu Khalifeh:** Supervision, Writing – review & editing. **Mohamad Ramadan:** Supervision, Writing – review & editing. **Mohammed Ghazal:** Supervision, Writing – review & editing.

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.

Data availability

No data was used for the research described in the article.

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References

Aswathi Mohan, A., Robert Antony, A., Greeshma, K., Yun, J.H., Ramanan, R., Kim, H.S., 2022. Algal biopolymers as sustainable resources for a net-zero carbon bioeconomy. Bioresour. Technol. 344, 126397 https://doi.org/10.1016/J.BIORTECH.2021.126397.

Ayub, H.M.U., Ahmed, A., Lam, S.S., Lee, J., Show, P.L., Park, Y.K., 2022. Sustainable valorization of algae biomass via thermochemical processing route: an overview. Bioresour. Technol. 344, 126399 https://doi.org/10.1016/J.BIORTECH.2021.126399.

Baskar, A.V., Singh, G., Ruban, A.M., Davidraj, J.M., Bahadur, R., Sooriyakumar, P., Kumar, P., Karakoti, A., Yi, J., Vinu, A., 2023. Recent progress in synthesis and application of biomass-based hybrid electrodes for rechargeable batteries. Adv. Funct. Mater. 33, 2208349. https://doi.org/10.1002/adfm.202208349.

Bie, Y., Yang, J., Nuli, Y., Wang, J., 2017. Natural karaya gum as an excellent binder for silicon-based anodes in high-performance lithium-ion batteries. J. Mater. Chem. A Mater. 5, 1919–1924. https://doi.org/10.1039/C6TA09522D.

Casimir, A., Zhang, H., Ogoke, O., Amine, J.C., Lu, J., Wu, G., 2016. Silicon-based anodes for lithium-ion batteries: effectiveness of materials synthesis and electrode preparation. Nano Energy 27, 359–376. https://doi.org/10.1016/j.nanoen.2016.07.023.

Chen, J., Liu, W., Liu, S., Wang, H., Zhang, Y., Chen, S., 2017. Marine microalgaes-derived porous ZnMn 2 O 4 /C microspheres and performance evaluation as Li-ion battery Anode by using different binders. Chem. Eng. J. 308, 1200–1208. https://doi.org/10.1016/j.cej.2016.09.144.

Chen, J., Dai, L., Mataya, D., Cobb, K., Chen, P., Ruan, R., 2022. Enhanced sustainable integration of CO2 utilization and wastewater treatment using microalgae in circular economy concept. Bioresour. Technol. 366, 128188 https://doi.org/10.1016/J.BIORTECH.2022.128188.

Chitra, R., Sathya, P., Selvasekarapandian, S., Monisha, S., Moniha, V., Meyvel, S., 2019. Synthesis and characterization of iota-carrageenan solid biopolymer electrolytes for electrochemical applications. Ionics (kiel) 25, 2147–2157. https://doi.org/10.1007/s11581-018-2687-z.

Chitra, R., Sathya, P., Selvasekarapandian, S., Meyvel, S., 2020a. Synthesis and characterization of iota-carrageenan biopolymer electrolyte with lithium perchlorate and succinonitrile (plasticizer). Polym. Bull. 77, 1555–1579. https://doi.org/10.1007/s00289-019-02822-y.

Chitra, R., Sathya, P., Selvasekarapandian, S., Meyvel, S., 2020b. Investigation of seaweed derivative iota-carrageenan based biopolymer electrolytes with lithium trifluoromethanesulfonate. Mater. Res. Express 7, 015309. https://doi.org/10.1088/2053-1591/ab5d79.

Cuesta, N., Ramos, A., Cameán, I., Antuña, C., García, A.B., 2015. Hydrocolloids as binders for graphite anodes of lithium-ion batteries. Electrochim. Acta 155, 140–147. https://doi.org/10.1016/j.electacta.2014.12.122.

Dang, B.T., Bui, X.T., Tran, D.P.H., Hao Ngo, H., Nghiem, L.D., Hoang, T.K.D., Nguyen, P. T., Nguyen, H.H., Vo, T.K.Q., Lin, C., Yi Andrew Lin, K., Varjani, S., 2022. Current application of algae derivatives for bioplastic production: a review. Bioresour. Technol. 347, 126698 https://doi.org/10.1016/J.BIORTECH.2022.126698.

De Tommasi, E., Gielis, J., Rogato, A., 2017. Diatom frustule morphogenesis and function: a multidisciplinary survey. Mar. Genomics 35, 1–18. https://doi.org/10.1016/j.margen.2017.07.001.

Devadas, V.V., Khoo, K.S., Chia, W.Y., Chew, K.W., Munawaroh, H.S.H., Lam, M.K., Lim, J.W., Ho, Y.C., Lee, K.T., Show, P.L., 2021. Algae biopolymer towards sustainable circular economy. Bioresour. Technol. 325, 124702 https://doi.org/10.1016/J.BIORTECH.2021.124702.

Elliott, D.C., Biller, P., Ross, A.B., Schmidt, A.J., Jones, S.B., 2015. Hydrothermal liquefaction of biomass: developments from batch to continuous process. Bioresour. Technol. 178, 147–156. https://doi.org/10.1016/J.BIORTECH.2014.09.132.

Entwistle, J., Rennie, A., Patwardhan, S., 2018. A review of magnesiothermic reduction of silica to porous silicon for lithium-ion battery applications and beyond. J. Mater. Chem. A Mater. 6, 18344–18356. https://doi.org/10.1039/C8TA06370B.

Fan, P., Liu, H., Marosz, V., Samuels, N.T., Suib, S.L., Sun, L., Liao, L., 2021. High performance composite polymer electrolytes for lithium-ion batteries. Adv. Funct. Mater. 31, 2101380. https://doi.org/10.1002/adfm.202101380.

Feng, K., Li, M., Liu, W., Kashkooli, A.G., Xiao, X., Cai, M., Chen, Z., 2018. Silicon-based anodes for lithium-ion batteries: from fundamentals to practical applications. Small 14, 1702737. https://doi.org/10.1002/smll.201702737.

Fortune Business Insights, 2022. Lithium-Ion Battery Market. https://www.fortunebusinessinsights.com/industry-reports/lithium-ion-battery-market-100123.

Frost, R.L., Ding, Z., 2003. Controlled rate thermal analysis and differential scanning calorimetry of sepiolites and palygorskites. Thermochim. Acta 397, 119–128. https://doi.org/10.1016/S0040-6031(02)00228-9.

Fuzlin, A.F., Bakri, N.A., Sahraoui, B., Samsudin, A.S., 2020. Study on the effect of lithium nitrate in ionic conduction properties based alginate biopolymer electrolytes. Mater. Res. Express 7, 015902. https://doi.org/10.1088/2053-1591/ab57bb.

Gao, S., Yan, Y., Chen, G., 2016. External water-free approach toward TiO_2 nanoparticles embedded in biomass-derived nitrogen-doped carbon. ACS Sustain. Chem. Eng. 4, 844–850. https://doi.org/10.1021/acssuschemeng.5b00904.

García, A., Culebras, M., Collins, M.N., Leahy, J.J., 2018. Stability and rheological study of sodium carboxymethyl cellulose and alginate suspensions as binders for lithium ion batteries. J. Appl. Polym. Sci. 135, 46217. https://doi.org/10.1002/app.46217.

Hazaana, S.A., Joseph, A., Selvasekarapandian, S., Naachiyar, R.M., Vignesh, N.M., 2023. Performance of solid-state Li-ion conducting battery using biopolymer electrolyte based on agar–agar/lithium chloride. J. Solid State Electrochem. 27, 539–557. https://doi.org/10.1007/s10008-022-05348-y.

Huang, Y., Lin, Z., Zheng, M., Wang, T., Yang, J., Yuan, F., Lu, X., Liu, L., Sun, D., 2016. Amorphous Fe2O3 nanoshells coated on carbonized bacterial cellulose nanofibers as a flexible anode for high-performance lithium ion batteries. J. Power Sources 307, 649–656. https://doi.org/10.1016/j.jpowsour.2016.01.026.

Huang, H., Shi, C., Fang, R., Xia, Y., Liang, C., Gan, Y., Zhang, J., Tao, X., Zhang, W., 2019. Bio-templated fabrication of MnO nanoparticles in SiOC matrix with lithium storage properties. Chem. Eng. J. 359, 584–593. https://doi.org/10.1016/j.cej.2018.11.166.

Hwang, G., Kim, J.-M., Hong, D., Kim, C.-K., Choi, N.-S., Lee, S.-Y., Park, S., 2016. Multifunctional natural agarose as an alternative material for high-performance rechargeable lithium-ion batteries. Green Chem. 18, 2710–2716. https://doi.org/10.1039/C5GC02654G.

Illa Font, C.H., Siqueira, H.V., Machado Neto, J.E., dos Santos, J.L.F., Stevan, S.L., Converti, A., Corrêa, F.C., 2023. Second life of lithium-ion batteries of electric vehicles: a short review and perspectives. Energies (basel) 16, 953. https://doi.org/10.3390/en16020953.

Jeong, Y.K., Kwon, T., Lee, I., Kim, T.-S., Coskun, A., Choi, J.W., 2015. Millipede-inspired structural design principle for high performance polysaccharide binders in silicon anodes. Energ. Environ. Sci. 8, 1224–1230. https://doi.org/10.1039/C5EE00239G.

Jin, C., Nai, J., Sheng, O., Yuan, H., Zhang, W., Tao, X., Lou, X.W. (David), 2021. Biomass-based materials for green lithium secondary batteries. Energ. Environ. Sci. 14, 1326–1379. https://doi.org/10.1039/D0EE02848G.

Kanna Dasan, Y., Lam, M.K., Chai, Y.H., Lim, J.W., Ho, Y.C., Tan, I.S., Lau, S.Y., Show, P. L., Lee, K.T., 2023. Unlocking the potential of microalgae bio-factories for carbon dioxide mitigation: a comprehensive exploration of recent advances, key challenges, and energy-economic insights. Bioresour. Technol. 380, 129094 https://doi.org/10.1016/J.BIORTECH.2023.129094.

Kant Bhatia, S., Ahuja, V., Chandel, N., Gurav, R., Kant Bhatia, R., Govarthanan, M., Kumar Tyagi, V., Kumar, V., Pugazendhi, A., Rajesh Banu, J., Yang, Y.H., 2022. Advances in algal biomass pretreatment and its valorisation into biochemical and bioenergy by the microbial processes. Bioresour. Technol. 358, 127437 https://doi.org/10.1016/J.BIORTECH.2022.127437.

Kartik, A., Akhil, D., Lakshmi, D., Panchamoorthy Gopinath, K., Arun, J., Sivaramakrishnan, R., Pugazhendhi, A., 2021. A critical review on production of biopolymers from algae biomass and their applications. Bioresour. Technol. 329, 124868 https://doi.org/10.1016/J.BIORTECH.2021.124868.

Kovalenko, I., Zdyrko, B., Magasinski, A., Hertzberg, B., Milicev, Z., Burtovyy, R., Luzinov, I., Yushin, G., 2011. A major constituent of brown algae for use in high-capacity Li-Ion batteries. Science 1979 (334), 75–79. https://doi.org/10.1126/science.1209150.

Kwon, K.M., Kim, I.G., Lee, K.-Y., Kim, H., Kim, M.S., Cho, W.I., Choi, J., Nah, I.W., 2019. α-Fe2O3 anchored on porous N doped carbon derived from green microalgae via spray pyrolysis as anode materials for lithium ion batteries. J. Ind. Eng. Chem. 69, 39–47. https://doi.org/10.1016/j.jiec.2018.09.004.

Lander, L., Cleaver, T., Rajaeifar, M.A., Nguyen-Tien, V., Elliott, R.J.R., Heidrich, O., Kendrick, E., Edge, J.S., Offer, G., 2021. Financial viability of electric vehicle lithium-ion battery recycling. iScience 24, 102787. https://doi.org/10.1016/j.isci.2021.102787.

Leo Edward, M., Dharanibalaji, K.C., Kumar, K.T., Chandrabose, A.R.S., Shanmugharaj, A.M., Jaisankar, V., 2022. Preparation and characterisation of chitosan extracted from shrimp shell (Penaeus monodon) and chitosan-based blended solid polymer electrolyte for lithium-ion batteries. Polym. Bull. 79, 587–604. https://doi.org/10.1007/s00289-020-03472-1.

Leong, Y.K., Chang, J.S., 2023. Microalgae-based biochar production and applications: a comprehensive review. Bioresour. Technol. 389, 129782 https://doi.org/10.1016/J.BIORTECH.2023.129782.

Leong, Y.K., Chen, C.Y., Varjani, S., Chang, J.S., 2022. Producing fucoxanthin from algae – recent advances in cultivation strategies and downstream processing. Bioresour. Technol. 344, 126170 https://doi.org/10.1016/J.BIORTECH.2021.126170.

Li, D., Chang, G., Zong, L., Xue, P., Wang, Y., Xia, Y., Lai, C., Yang, D., 2019. From double-helix structured seaweed to S-doped carbon aerogel with ultra-high surface area for energy storage. Energy Storage Mater. 17, 22–30. https://doi.org/10.1016/j.ensm.2018.08.004.

Li, L., Zhang, D., Deng, J., Gou, Y., Fang, J., Cui, H., Zhao, Y., Cao, M., 2021. Carbon-based materials for fast charging lithium-ion batteries. Carbon N. Y. 183, 721–734. https://doi.org/10.1016/j.carbon.2021.07.053.

Liang, C., Gao, M., Pan, H., Liu, Y., Yan, M., 2013. Lithium alloys and metal oxides as high-capacity anode materials for lithium-ion batteries. J. Alloy. Compd. 575, 246–256. https://doi.org/10.1016/j.jallcom.2013.04.001.

Ling, M., Xu, Y., Zhao, H., Gu, X., Qiu, J., Li, S., Wu, M., Song, X., Yan, C., Liu, G., Zhang, S., 2015. Dual-functional gum arabic binder for silicon anodes in lithium ion batteries. Nano Energy 12, 178–185. https://doi.org/10.1016/j.nanoen.2014.12.011.

Lisowska-Oleksiak, A., Nowak, A.P., Wicikowska, B., 2014. Aquatic biomass containing porous silica as an anode for lithium ion batteries. RSC Adv. 4, 40439–40443. https://doi.org/10.1039/C4RA06420H.

Liu, W.-R., Yang, M.-H., Wu, H.-C., Chiao, S.M., Wu, N.-L., 2005. Enhanced cycle life of Si anode for Li-ion batteries by using modified elastomeric binder. Electrochem. Solid St. 8, A100. https://doi.org/10.1149/1.1847685.

Liu, J., Zhang, Q., Zhang, T., Li, J.-T., Huang, L., Sun, S.-G., 2015. A robust ion-conductive biopolymer as a binder for Si anodes of lithium-ion batteries. Adv. Funct. Mater. 25, 3599–3605. https://doi.org/10.1002/adfm.201500589.

Long, W., Fang, B., Ignaszak, A., Wu, Z., Wang, Y.-J., Wilkinson, D., 2017. Biomass-derived nanostructured carbons and their composites as anode materials for lithium ion batteries. Chem. Soc. Rev. 46, 7176–7190. https://doi.org/10.1039/C6CS00639F.

Lu, M., Yu, W., Shi, J., Liu, W., Chen, S., Wang, X., Wang, H., 2017. Self-doped carbon architectures with heteroatoms containing nitrogen, oxygen and sulfur as high-performance anodes for lithium- and sodium-ion batteries. Electrochim. Acta 251, 396–406. https://doi.org/10.1016/j.electacta.2017.08.131.

Lv, F., Wang, Z., Shi, L., Zhu, J., Edström, K., Mindemark, J., Yuan, S., 2019. Challenges and development of composite solid-state electrolytes for high-performance lithium ion batteries. J. Power Sources 441, 227175. https://doi.org/10.1016/j.jpowsour.2019.227175.

Mobarak, N.N., Jumaah, F.N., Ghani, M.A., Abdullah, M.P., Ahmad, A., 2015. Carboxymethyl carrageenan based biopolymer electrolytes. Electrochim. Acta 175, 224–231. https://doi.org/10.1016/j.electacta.2015.02.200.

Nagendranatha Reddy, C., Nguyen, H.T.H., Noori, M.T., Min, B., 2019. Potential applications of algae in the cathode of microbial fuel cells for enhanced electricity generation with simultaneous nutrient removal and algae biorefinery: Current status and future perspectives. Bioresour. Technol. 292, 122010 https://doi.org/10.1016/J.BIORTECH.2019.122010.

Noura, N., Boulon, L., Jemeï, S., 2020. A review of battery state of health estimation methods: hybrid electric vehicle challenges. World Electric Vehicle J. 11, 66. https://doi.org/10.3390/wevj11040066.

Nowak, A.P., Sprynskyy, M., Brzozowska, W., Lisowska-Oleksiak, A., 2019. Electrochemical behavior of a composite material containing 3D-structured diatom biosilica. Algal Res. 41, 101538 https://doi.org/10.1016/j.algal.2019.101538.

Nzereogu, P.U., Omah, A.D., Ezema, F.I., Iwuoha, E.I., Nwanya, A.C., 2022. Anode materials for lithium-ion batteries: a review. Appl. Surf. Sci. Adv. 9, 100233 https://doi.org/10.1016/j.apsadv.2022.100233.

Park, S., Song, J., Lee, W.C., Jang, S., Lee, J., Kim, J., Kim, H.-K., Min, K., 2023. Advances in biomass-derived electrode materials for energy storage and circular carbon economy. Chem. Eng. J. 470, 144234 https://doi.org/10.1016/j.cej.2023.144234.

Parsimehr, H., Ehsani, A., 2020. Algae-based electrochemical energy storage devices. Green Chem. 22, 8062–8096. https://doi.org/10.1039/D0GC02246B.

Pathy, A., Nageshwari, K., Ramaraj, R., Pragas Maniam, G., Govindan, N., Balasubramanian, P., 2022. Biohydrogen production using algae: Potentiality, economics and challenges. Bioresour. Technol. 360, 127514 https://doi.org/10.1016/J.BIORTECH.2022.127514.

Raza, A., Ghani, F., Lim, J., Nah, I.W., Kim, H.-S., 2021. Eco-friendly prepared mesoporous carbon encapsulated SnO2 nanoparticles for high-reversible lithium-ion battery anodes. Micropor. Mesopor. Mater. 314, 110853 https://doi.org/10.1016/j.micromeso.2020.110853.

Renman, V., Blanco, M.V., Norberg, A.N., Vullum-Bruer, F., Svensson, A.M., 2021. Electrochemical activation of a diatom-derived SiO2/C composite anode and its implementation in a lithium ion battery. Solid State Ion. 371, 115766 https://doi.org/10.1016/j.ssi.2021.115766.

Roselin, L.S., Juang, R.-S., Hsieh, C.-T., Sagadevan, S., Umar, A., Selvin, R., Hegazy, H.H., 2019. Recent advances and perspectives of carbon-based nanostructures as anode

materials for Li-ion batteries. Materials 12, 1229. https://doi.org/10.3390/ma12081229.
Ru, H., Bai, N., Xiang, K., Zhou, W., Chen, H., Zhao, X.S., 2016. Porous carbons derived from microalgae with enhanced electrochemical performance for lithium-ion batteries. Electrochim. Acta 194, 10–16. https://doi.org/10.1016/j.electacta.2016.02.083.
Salimi, P., Javadian, S., Norouzi, O., Gharibi, H., 2017. Turning an environmental problem into an opportunity: potential use of biochar derived from a harmful marine biomass named Cladophora glomerata as anode electrode for Li-ion batteries. Environ. Sci. Pollut. Res. 24, 27974–27984. https://doi.org/10.1007/s11356-017-0181-1.
Selvalakshmi, S., Vijaya, N., Selvasekarapandian, S., Premalatha, M., 2017. Biopolymer agar-agar doped with NH_4 SCN as solid polymer electrolyte for electrochemical cell application. J. Appl. Polym. Sci. 134 https://doi.org/10.1002/app.44702.
Seo, J.-C., Umirov, N., Park, S.B., Lee, K., Kim, S.-S., 2019. Microalgae-derived hollow carbon-MoS2 composite as anode for lithium-ion batteries. J. Ind. Eng. Chem. 79, 106–114. https://doi.org/10.1016/j.jiec.2019.05.046.
Singh, V., Kuthe, S., Skorodumova, N.V., 2023. Electrode fabrication techniques for Li ion based energy storage system: a review. Batteries 9, 184. https://doi.org/10.3390/batteries9030184.
Song, Q., Li, A., Shi, L., Qian, C., Feric, T.G., Fu, Y., Zhang, H., Li, Z., Wang, P., Li, Z., Zhai, H., Wang, X., Dontigny, M., Zaghib, K., Park, A.-H. (Alissa), Myers, K., Chuan, X., Yang, Y., 2019. Thermally stable, nano-porous and eco-friendly sodium alginate/attapulgite separator for lithium-ion batteries. Energy Storage Mater. 22, 48–56. https://doi.org/10.1016/j.ensm.2019.06.033.
Song, D., Park, J., Kim, K., Lee, L.S., Seo, J.Y., Oh, Y.-K., Kim, Y.-J., Ryou, M.-H., Lee, Y. M., Lee, K., 2017. Recycling oil-extracted microalgal biomass residues into nano/micro hierarchical Sn/C composite anode materials for lithium-ion batteries. Electrochim. Acta 250, 59–67. https://doi.org/10.1016/j.electacta.2017.08.045.
Sun, J., Norouzi, O., Mašek, O., 2022. A state-of-the-art review on algae pyrolysis for bioenergy and biochar production. Bioresour. Technol. 346, 126258 https://doi.org/10.1016/J.BIORTECH.2021.126258.
Tan, L., Li, Z., Shi, R., Quan, F., Wang, B., Ma, X., Ji, Q., Tian, X., Xia, Y., 2020. Preparation and properties of an alginate-based fiber separator for lithium-ion batteries. ACS Appl. Mater. Interfaces 12, 38175–38182. https://doi.org/10.1021/acsami.0c10630.
Tao, X., Wu, R., Xia, Y., Huang, H., Chai, W., Feng, T., Gan, Y., Zhang, W., 2014. Biotemplated fabrication of Sn@C anode materials based on the unique metal biosorption behavior of microalgae. ACS Appl. Mater. Interfaces 6, 3696–3702. https://doi.org/10.1021/am500020e.
Temeche, E., Laine, R.M., 2022. Solid electrolytes for lithium-sulfur batteries. In: Lithium-Sulfur Batteries. Elsevier, pp. 17–47. https://doi.org/10.1016/B978-0-12-819676-2.00008-6.
Torres, F.G., De-la-Torre, G.E., 2022. Green algae as a sustainable source for energy generation and storage technologies. Sustain. Energy Technol. Assess. 53, 102658 https://doi.org/10.1016/j.seta.2022.102658.
Vo Hoang Nhat, P., Ngo, H.H., Guo, W.S., Chang, S.W., Nguyen, D.D., Nguyen, P.D., Bui, X.T., Zhang, X.B., Guo, J.B., 2018. Can algae-based technologies be an affordable green process for biofuel production and wastewater remediation? Bioresour. Technol. 256, 491–501. https://doi.org/10.1016/J.BIORTECH.2018.02.031.
Wang, J., Liu, W., Chen, J., Wang, H., Liu, S., Chen, S., 2016. Biotemplated MnO/C microtubes from spirogyra with improved electrochemical performance for lithium-ion batterys. Electrochim. Acta 188, 210–217. https://doi.org/10.1016/j.electacta.2015.11.128.
Wang, L., Xue, J., Gao, B., Gao, P., Mou, C., Li, J., 2014. Rice husk derived carbon–silica composites as anodes for lithium ion batteries. RSC Adv. 4, 64744–64746. https://doi.org/10.1039/C4RA09627D.
Wang, L., Xie, X., Dinh, K.N., Yan, Q., Ma, J., 2019. Synthesis, characterizations, and utilization of oxygen-deficient metal oxides for lithium/sodium-ion batteries and supercapacitors. Coord. Chem. Rev. 397, 138–167. https://doi.org/10.1016/j.ccr.2019.06.015.
Wang, Z., Xu, C., Tammela, P., Huo, J., Strømme, M., Edström, K., Gustafsson, T., Nyholm, L., 2015. Flexible freestanding Cladophora nanocellulose paper based Si anodes for lithium-ion batteries. J. Mater. Chem. A Mater. 3, 14109–14115. https://doi.org/10.1039/C5TA02136G.
Wang, C., Zhu, G., Hu, Y., Sun, J., Xu, J., Wang, L., Wang, H., Cheng, C., 2023. Ionic conductivity and cycling stability-enhanced composite separator using hollow halloysite nanotubes constructed on PP nonwoven through polydopamine-induced water-based coating method. Colloids Surf. A Physicochem. Eng. Asp. 667, 131403 https://doi.org/10.1016/j.colsurfa.2023.131403.
Wei, L., Karahan, H.E., Zhai, S., Yuan, Y., Qian, Q., Goh, K., Ng, A.K., Chen, Y., 2016. Microbe-derived carbon materials for electrical energy storage and conversion. J. Energy Chem. 25, 191–198. https://doi.org/10.1016/j.jechem.2015.12.001.
Wen, H., Zhang, J., Chai, J., Ma, J., Yue, L., Dong, T., Zang, X., Liu, Z., Zhang, B., Cui, G., 2017. Sustainable and superior heat-resistant alginate nonwoven separator of LiNi $_{0.5}$ Mn $_{1.5}$ O 4 /Li batteries operated at 55 °C. ACS Appl. Mater. Interfaces 9, 3694–3701. https://doi.org/10.1021/acsami.6b14352.
Wu, Z.-Y., Deng, L., Li, J.-T., Huang, Q.-S., Lu, Y.-Q., Liu, J., Zhang, T., Huang, L., Sun, S.-G., 2017. Multiple hydrogel alginate binders for Si anodes of lithium-ion battery. Electrochim. Acta 245, 371–378. https://doi.org/10.1016/j.electacta.2017.05.094.
Wu, F., Huang, R., Mu, D., Wu, B., Chen, Y., 2016. Controlled synthesis of graphitic carbon-encapsulated α-Fe2O3 nanocomposite via low-temperature catalytic graphitization of biomass and its lithium storage property. Electrochim. Acta 187, 508–516. https://doi.org/10.1016/j.electacta.2015.11.108.
Wu, J., Ma, F., Liu, X., Fan, X., Shen, L., Wu, Z., Ding, X., Han, X., Deng, Y., Hu, W., Zhong, C., 2019. Recent progress in advanced characterization methods for silicon-based lithium-ion batteries. Small Methods 3, 1900158. https://doi.org/10.1002/smtd.201900158.
Xia, Y., Xiao, Z., Dou, X., Huang, H., Lu, X., Yan, R., Gan, Y., Zhu, W., Tu, J., Zhang, W., Tao, X., 2013. Green and facile fabrication of hollow porous MnO/C microspheres from microalgaes for lithium-ion batteries. ACS Nano 7, 7083–7092. https://doi.org/10.1021/nn4023894.
Xia, Y., Fang, R., Xiao, Z., Ruan, L., Yan, R., Huang, H., Liang, C., Gan, Y., Zhang, J., Tao, X., Zhang, W., 2016. Supercritical fluid assisted biotemplating synthesis of Si–O–C microspheres from microalgae for advanced Li-ion batteries. RSC Adv. 6, 69764–69772. https://doi.org/10.1039/C6RA13560A.
Xu, J., Chou, S.-L., Gu, Q., Liu, H.-K., Dou, S.-X., 2013. The effect of different binders on electrochemical properties of LiNi1/3Mn1/3Co1/3O2 cathode material in lithium ion batteries. J. Power Sources 225, 172–178. https://doi.org/10.1016/j.jpowsour.2012.10.033.
Xu, H., Zhang, H., Ouyang, Y., Liu, L., Wang, Y., 2016a. Two-dimensional hierarchical porous carbon composites derived from corn stalks for electrode materials with high performance. Electrochim. Acta 214, 119–128. https://doi.org/10.1016/j.electacta.2016.08.043.
Xu, H., Zhang, S., He, W., Zhang, X., Yang, G., Zhang, J., Shi, X., Wang, L., 2016b. SiO_2-carbon nanocomposite anodes with a 3D interconnected network and porous structure from bamboo leaves. RSC Adv. 6, 1930–1937. https://doi.org/10.1039/C5RA19961A.
Ye, H., Zheng, G., Yang, X., Zhang, D., Zhang, Y., Yan, S., You, L., Hou, S., Huang, Z., 2021. Application of different carbon-based transition metal oxide composite materials in lithium-ion batteries. J. Electroanal. Chem. 898, 115652 https://doi.org/10.1016/j.jelechem.2021.115652.
Yu, J., Tang, T., Cheng, F., Huang, D., Martin, J.L., Brewer, C.E., Grimm, R.L., Zhou, M., Luo, H., 2021. Exploring spent biomass-derived adsorbents as anodes for lithium ion batteries. Mater. Today Energy 19, 100580. https://doi.org/10.1016/j.mtener.2020.100580.
Yu, J., Audu, M., Myint, M.T., Cheng, F., Jarvis, J.M., Jena, U., Nirmalakhandan, N., Brewer, C.E., Luo, H., 2022. Bio-crude oil production and valorization of hydrochar as anode material from hydrothermal liquefaction of algae grown on brackish dairy wastewater. Fuel Process. Technol. 227, 107119 https://doi.org/10.1016/j.fuproc.2021.107119.
Yu, K.L., Lau, B.F., Show, P.L., Ong, H.C., Ling, T.C., Chen, W.H., Ng, E.P., Chang, J.S., 2017. Recent developments on algal biochar production and characterization. Bioresour. Technol. 246, 2–11. https://doi.org/10.1016/J.BIORTECH.2017.08.009.
Yuan, S., Lai, Q., Duan, X., Wang, Q., 2023. Carbon-based materials as anode materials for lithium-ion batteries and lithium-ion capacitors: a review. J. Energy Storage 61, 106716. https://doi.org/10.1016/j.est.2023.106716.
Zhang, S., Deng, Y., Wu, Q., Zhou, Y., Li, J., Wu, Z., Yin, Z., Lu, Y., Shen, C., Huang, L., Sun, S., 2018. Sodium-alginate-based binders for lithium-rich cathode materials in lithium-ion batteries to suppress voltage and capacity fading. ChemElectroChem 5, 1321–1329. https://doi.org/10.1002/celc.201701358.
Zhang, J.-G., Wang, W., Xiao, J., Xu, W., Graff, G.L., Yang, G., Choi, D., Wang, D., Li, X., Liu, J., 2012. Silicon-Based Anodes for Li-Ion Batteries, in: Encyclopedia of Sustainability Science and Technology. Springer New York, New York, NY, pp. 9293–9316. https://doi.org/10.1007/978-1-4419-0851-3_496.
Zhang, S., Ren, S., Han, D., Xiao, M., Wang, S., Meng, Y., 2019. Aqueous sodium alginate as binder: dramatically improving the performance of dilithium terephthalate-based organic lithium ion batteries. J. Power Sources 438, 227007. https://doi.org/10.1016/j.jpowsour.2019.227007.
Zhang, C., Wang, F., Han, J., Bai, S., Tan, J., Liu, J., Li, F., 2021. Challenges and recent progress on silicon-based anode materials for next-generation lithium-ion batteries. Small Struct. 2, 2100009. https://doi.org/10.1002/sstr.202100009.
Zhang, T., Zhu, C., Shi, Y., Li, Y., Zhu, S., Zhang, D., 2017. Synthesis of Fe2O3 in situ on the surface of mesoporous carbon from alginate as a high-performance anode for lithium-ion batteries. Mater. Lett. 205, 10–14. https://doi.org/10.1016/j.matlet.2017.06.020.
Zhao, Y., Li, X., Yan, B., Xiong, D., Li, D., Lawes, S., Sun, X., 2016. Recent developments and understanding of novel mixed transition-metal oxides as anodes in lithium ion batteries. Adv. Energy Mater. 6, 1502175. https://doi.org/10.1002/aenm.201502175.
Zhou, Y., Liu, L., Li, M., Hu, C., 2022. Algal biomass valorisation to high-value chemicals and bioproducts: recent advances, opportunities and challenges. Bioresour. Technol. 344, 126371 https://doi.org/10.1016/J.BIORTECH.2021.126371.