SJESC
Souf Journal of Engineering and Sustainable Chemistry
Souf Journal of Engineering and Sustainable Chemistry (SJESC)
ISSN:3088-831X
2026. Vol. 2, N°.1, 047-066
Journal homepage: https://sjescjournal.com

Review

Biopolymer Hydrogels, Biochar, and Bio-based Plastics: A Review

Boughezala Hamad Omayma[1], Djouadi Nadia[1*], Leghrieb Ikhlasse [1], Rebbouh Rodaina[1], Kired Chaima[1]

[1]Department of Process Engineering and Petrochemical, Faculty of Technology, University of El Oued, El Oued 39000, Algeria
*****Correspondence: nadadjouadi02@gmail.com

Article Information

Article History
Received : 24-03-2026
Revised : 14-05-2026
Accepted : 22-05-2026

Keywords: Biopolymer hydrogels, Biochar, Bio-based plastics, Sustainable materials; Agricultural waste valorization

Abstract

Growing environmental concerns regarding traditional petroleum-derived materials have led to increased research interest in sustainable alternatives derived from renewable resources. This review provides a comprehensive overview of three main types of biomaterials: biopolymer hydrogels, biochar, and bioplastics. Despite their different compositions and manufacturing methods, biopolymer hydrogels, biochar, and bioplastics share a common goal: producing sustainable, practical, and environmentally compatible materials. Key challenges remain, including improving mechanical performance, ensuring scalability, and achieving long-term stability. By addressing these limitations through integrated design strategies, these biomaterials hold great promise for advancing the circular bioeconomy and reducing the environmental impact of material consumption across various industries.

1. Introduction

The escalating volume of agricultural waste generated worldwide constitutes both an environmental challenge and a valuable untapped resource. Residues such as crop stalks, fruit peels, bagasse, rice husks, and animal manure are produced in billions of tons annually, often burned or discarded, contributing to air pollution, greenhouse gas emissions, and soil degradation[1]. In parallel, the global demand for sustainable materials is rapidly increasing due to the environmental footprint of petroleum-based plastics, synthetic hydrogels, and non-renewable carbon materials. Valorization of agricultural biomass into high-value biomaterials therefore represents a strategic pathway toward circular bioeconomy models that simultaneously address waste management, resource efficiency, and climate change mitigation[2, 3, 4].

Biopolymer-based hydrogels, biochar, and bioplastics have emerged as three particularly promising classes of materials derivable from agricultural residues. Hydrogels produced from polysaccharides (starch, cellulose, chitosan, alginate) and proteins exhibit exceptional water-holding capacity, stimuli-responsiveness, and biocompatibility, making them suitable for soil conditioning, controlled agrochemical release, and even energy storage applications [5, 6]. Biochar, obtained through thermochemical conversion (primarily pyrolysis), provides long-term carbon sequestration, soil fertility enhancement, and pollutant adsorption[7] **.** Bioplastics, ranging from polysaccharide-based films to microbially produced polyhydroxyalkanoates (PHAs), offer renewable and potentially biodegradable alternatives to conventional plastics in

packaging, healthcare, and technical applications [8].Despite individual progress in each field, integrated studies that simultaneously address hydrogels, biochar, and bioplastics from the same agricultural feedstocks remain limited. Such an approach could unlock synergies (e.g., using biochar as a filler in bioplastic composites or hydrogel precursors in biochar activation) and maximize resource efficiency within biorefinery concepts.

This review therefore aims to provide a structured overview of fabrication methods, key properties, and current & emerging environmental/agricultural applications of hydrogels, biochar, and bioplastics derived from agricultural waste. By highlighting both achievements and existing gaps, the article seeks to guide future research toward more holistic and scalable valorization strategies aligned with global sustainability goals.

2. Biopolymer Hydrogels

Biohydrogels are three-dimensional, highly hydrated crosslinked networks primarily formed from natural biopolymers such as polysaccharides (e.g., alginate, chitosan, hyaluronic acid, starch, guar gum, cellulose) and proteins (e.g., collagen, gelatin, silk fibroin, fibrin).

2.1. Fabrication Techniques

The fabrication of biopolymer hydrogel scaffolds relies on sophisticated manufacturing approaches that enable precise modulation of their physicochemical and structural properties. A pivotal stage in this process is crosslinking, which critically governs key scaffold attributes including mechanical strength, structural stability, and degradation kinetics [9]. By establishing covalent or non-covalent interactions between polymer chains, crosslinking enhances the hydrogel's architectural robustness, thereby optimizing its performance in diverse biomedical contexts particularly tissue engineering, controlled drug release, and regenerative wound care. Crosslinking strategies are broadly categorized into two principal approaches: chemical crosslinking, which involves the formation of stable covalent bonds, and physical crosslinking, which relies on reversible non-covalent interactions such as hydrogen bonding, electrostatic forces, or hydrophobic associations.

2.1.1. Electrospinning Method

Electrospinning has emerged as a versatile and widely adopted fabrication technique for producing biopolymer-based hydrogel scaffolds, particularly in the fields of tissue engineering and regenerative medicine. Its principal advantage lies in the ability to generate fibrous architectures with fiber diameters spanning the nanometer to micrometer range, closely mimicking the topographical and structural features of the native extracellular matrix (ECM). This biomimetic resemblance fosters an optimal microenvironment that supports cellular adhesion, proliferation, and differentiation [10].

The process involves subjecting a polymer solution to a high-voltage electrostatic field. Typically, natural biopolymers such as alginate, chitosan, gelatin, or hyaluronic acid are dissolved in suitable solvents, often in combination with crosslinking agents or stabilizers to enhance mechanical resilience and hydration capacity [11]. The solution is loaded into a syringe

fitted with a metallic needle, positioned opposite a grounded collector. Upon application of voltage, electrostatic forces overcome the solution's surface tension, initiating the formation of a charged jet that undergoes rapid elongation and solvent evaporation during its trajectory toward the collector. The resulting deposit consists of ultrafine, non-woven fibers characterized by high surface-area-to-volume ratios and interconnected porosity features essential for facilitating cell infiltration, nutrient diffusion, and waste removal [12].

Key morphological and mechanical properties of the electrospun scaffold including fiber diameter, pore size distribution, and fiber alignment can be precisely tuned by modulating process parameters such as polymer concentration, solution viscosity, applied voltage magnitude, flow rate, and the distance between the needle tip and collector. This tunability enables the design of scaffolds with tailored mechanical behavior (e.g., stiffness or elasticity) to match the biomechanical demands of specific target tissues[13].

Post-fabrication crosslinking whether chemical (e.g., using glutaraldehyde) or physical (e.g., ionic crosslinking for alginate-based systems) is frequently employed to stabilize the fibrous network, enhance structural integrity, and modulate degradation kinetics in physiological environments [14]. Moreover, electrospinning permits the seamless incorporation of bioactive agents, such as growth factors, therapeutic drugs, or even viable cells, directly into the fibers during spinning. This capability facilitates the sustained and spatially controlled release of bioactive molecules, thereby augmenting the scaffold's regenerative functionality and therapeutic efficacy [15]. In summary, electrospinning stands out as a powerful and adaptable platform for engineering biopolymer hydrogel scaffolds. Its capacity to produce highly porous, biomimetic fibrous networks with customizable architecture, combined with the potential for functionalization with bioactive cues, renders it exceptionally suitable for advanced applications in tissue regeneration, wound management, and localized drug delivery systems.

2.1.2. Chemical Crosslinking Method

Chemical crosslinking represents a fundamental strategy for enhancing the structural stability, mechanical performance, and degradation profile of biopolymer hydrogels intended for biomedical applications. This technique involves the formation of covalent bonds between adjacent polymer chains, thereby generating a three-dimensional network that imparts robust mechanical integrity while enabling precise modulation of the hydrogel's physicochemical properties [16].

The process typically initiates with the selection of naturally derived biopolymers such as alginate, chitosan, collagen, or gelatin chosen for their inherent biocompatibility and biodegradability. Crosslinking is subsequently induced through the addition of bifunctional or multifunctional agents, including glutaraldehyde, genipin, or carbodiimide-based reagents (e.g., EDC/NHS), which catalyze the formation of stable covalent linkages between functional groups on the polymer backbone [17]. Critically, the extent of crosslinking can be finely regulated by adjusting parameters such as crosslinker concentration, reaction duration, pH, and temperature, thereby allowing systematic control over the scaffold's final architecture and performance characteristics[17].

A principal advantage of chemical crosslinking lies in its capacity to engineer hydrogels with tailored mechanical properties. By modulating crosslinking density, scaffolds can be

designed to exhibit specific stiffness, tensile strength, and viscoelastic behavior that closely emulate the biomechanical milieu of target tissues whether load-bearing cartilage and bone or compliant soft tissues .Concurrently, this approach enables precise tuning of hydrogel swelling behavior and water-holding capacity, which are vital for maintaining adequate nutrient diffusion, waste removal, and gas exchange to support embedded cell viability and function. Furthermore, the degradation kinetics of chemically crosslinked hydrogels can be strategically controlled through crosslinking density. Higher crosslinking densities generally yield networks with slower enzymatic or hydrolytic degradation rates, providing prolonged structural support during tissue maturation. Conversely, reduced crosslinking facilitates accelerated degradation that can be synchronized with the rate of neotissue formation, thereby preventing mechanical mismatch over time [18].

An additional asset of this methodology is its compatibility with biofunctionalization strategies. Bioactive moieties such as cell-adhesive peptides (e.g., RGD sequences), growth factors, or signaling molecules can be covalently conjugated to the polymer network during or after crosslinking. This is often achieved by pre-functionalizing polymer chains with reactive groups (e.g., amine, carboxyl, or thiol moieties) that enable site-specific immobilization of biomolecules, thereby enhancing cellular recognition, adhesion, and regenerative signaling within the scaffold microenvironment [19].

2.1.3. Three-Dimensional (3D) Printing Method

3D printing has revolutionized the fabrication of biopolymer hydrogel-based scaffolds in tissue engineering and regenerative medicine by enabling the precise, layer-by-layer construction of patient-specific architectures with intricate geometries. This additive manufacturing approach facilitates the design of scaffolds that accurately recapitulate the structural complexity and hierarchical organization of the native extracellular matrix (ECM), thereby providing an optimal microenvironment for cell adhesion, proliferation, and functional tissue regeneration [20].

The process begins with the formulation of printable hydrogel "bioinks," typically prepared by dissolving natural polymers such as alginate, chitosan, gelatin, hyaluronic acid, or collagen in biocompatible solvents to achieve rheological properties suitable for extrusion [21]. A central challenge in hydrogel-based 3D printing lies in balancing printability with structural fidelity: the bioink must possess sufficient viscosity and shear-thinning behavior to flow through the nozzle during extrusion, yet rapidly stabilize post-deposition to retain the intended architecture. This is commonly addressed by integrating crosslinking mechanisms either physical or chemical during or immediately after the printing process [22].

Several crosslinking strategies have been adapted for 3D printing applications. For instance, alginate-based bioinks often employ ionic crosslinking, wherein divalent cations (e.g., Ca^{2+}) are introduced either within the printing bath or as a co-axial crosslinking agent during extrusion, enabling instantaneous gelation while preserving high water content and interconnected porosity essential for nutrient diffusion [23]. Alternatively, thermoresponsive hydrogels such as gelatin-methacryloyl (GelMA) undergo thermal gelation upon cooling below their sol–gel transition temperature, allowing shape retention at physiological conditions following deposition.

A distinctive advantage of 3D printing is its capacity to engineer scaffolds with spatially controlled architectural features including pore size distribution, interconnectivity, channel alignment, and regional variations in mechanical properties thereby mimicking the anisotropic and heterogeneous nature of native tissues [24]. Moreover, the technique supports the direct incorporation of living cells, growth factors, and other bioactive cues into the bioink formulation, enabling the fabrication of cell-laden constructs capable of sustained, localized release of therapeutic agents to enhance regenerative outcomes [25]. This level of customization facilitates the design of tissue-specific scaffolds tailored to the biomechanical and biological requirements of diverse applications, ranging from load-bearing bone and cartilage to compliant soft tissues (see Figure 1).

The potential for patient-specific customization further amplifies the clinical relevance of 3D-printed hydrogels. For example, Lee et al.[26] developed a hybrid 3D-printed matrix integrating nanofibrillar components within a hydrogel network to simultaneously provide topographical contact guidance and a hydrated microenvironment mimicking native ECM conditions. Their construct enabled embedded cells to interact with both fibrillar structures and the surrounding aqueous phase, thereby modulating cellular morphology, adhesion, and spreading behavior. By correlating matrix erosion kinetics with evolving mechanical properties, the researchers demonstrated how nanofibril incorporation influences cell-mediated matrix remodeling a critical consideration for designing bioactive, cell-instructive scaffolds [27].

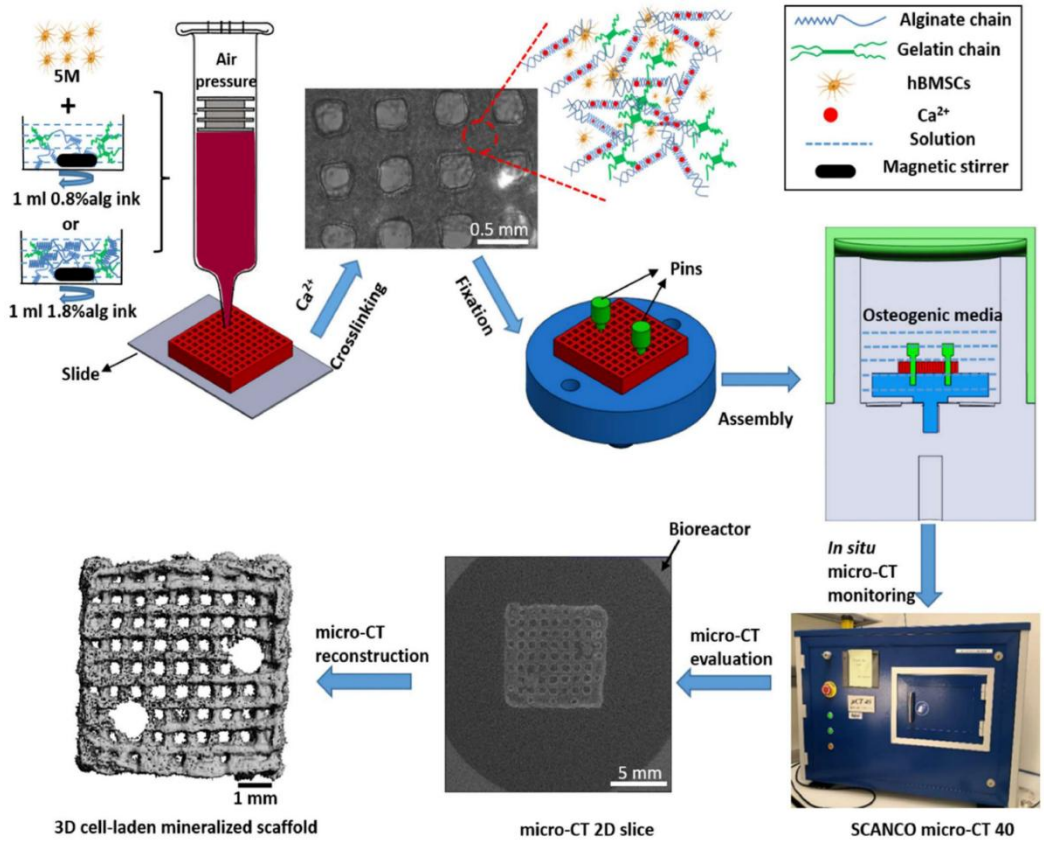

Fig. 1 Preparation of bio-inks with different concentrations of alginates, 3D bioprinting, crosslinking, bioreactor assembly, time-lapse computed tomography (CT) monitoring, CT micro-evaluation, and CT micro-reconstruction processes (Reproduced with permission from Zhang et al.[28]).

2.1.4. Physical Crosslinking Method

Physical crosslinking constitutes a versatile strategy for fabricating biopolymer hydrogel scaffolds through the establishment of non-covalent interactions including hydrogen bonding, ionic associations, hydrophobic interactions, and van der Waals forces thereby generating a three-dimensional polymeric network. In contrast to the permanent covalent linkages formed in chemical crosslinking, physically crosslinked networks exhibit reversible and dynamic behavior, rendering them responsive to environmental stimuli such as temperature, pH, ionic strength, and electric fields [29]. This stimuli-responsive nature makes physically crosslinked hydrogels particularly valuable for applications requiring adaptive behavior, including injectable tissue engineering constructs, on-demand drug delivery systems, and smart wound dressings.

The fabrication process typically begins with the dissolution of natural biopolymers such as alginate, chitosan, gelatin, or hyaluronic acid in an appropriate solvent to yield a homogeneous precursor solution. Gelation is subsequently induced by modulating external conditions to trigger network formation. For instance, alginate hydrogels undergo ionic crosslinking upon exposure to divalent cations (e.g., Ca^{2+}), which bridge guluronic acid residues via electrostatic interactions to form a stable yet reversible "egg-box" structure [30]. Similarly, thermoresponsive polymers like gelatin and agarose exhibit sol–gel transitions upon cooling, wherein reduced thermal energy promotes chain association and physical network formation through helix aggregation and hydrogen bonding.

A distinctive advantage of physical crosslinking lies in its inherent reversibility, which enables on-demand modulation of scaffold properties in response to physiological cues. Thermosensitive hydrogels, for example, can remain injectable at room temperature and rapidly gel upon reaching body temperature, facilitating minimally invasive delivery and in situ scaffold formation [31]. Moreover, the dynamic nature of non-covalent networks permits controlled release of encapsulated therapeutics or cells in response to specific microenvironmental triggers, enhancing spatiotemporal precision in drug delivery. Porosity, swelling ratio, and mechanical compliance can also be fine-tuned by adjusting crosslinking conditions, allowing the design of ECM-mimetic scaffolds that support cell infiltration and tissue ingrowth.

To overcome limitations in mechanical stability sometimes associated with purely physical networks, hybrid strategies combining physical and chemical crosslinking mechanisms have been developed. Wang et al. [32] engineered a dynamically crosslinked injectable hydrogel (DACS) by mixing dopamine-grafted oxidized hyaluronic acid (DAHA) with carboxymethyl chitosan (CMCS). Gelation occurred through a dual mechanism: Schiff base reactions between aldehyde groups on DAHA and amine groups on CMCS formed reversible imine bonds, while supplementary hydrogen bonding involving phenolic hydroxyl groups of grafted dopamine enhanced network cohesion yielding a mild, cytocompatible, and rapidly gelling system (see Figure 2a). In a complementary approach, Pan et al. [33] developed tough cellulose-based hydrogels (FBDC) using epoxidized vegetable oils as crosslinkers in a 75% ethanol medium. The covalent incorporation of flexible epoxidized oil domains imparted elasticity and deformability, while hydrogen bonding between cellulose chains and chain entanglement provided effective stress dissipation. The resulting hydrogel electrolyte exhibited exceptional

mechanical robustness (tensile strength: 6.1 MPa; elongation at break: 290%), high ionic conductivity (35.35 mS cm^{-1}), and electrochemical stability (2.4 V window), rendering it suitable for flexible wearable energy devices (see Figure 2b).

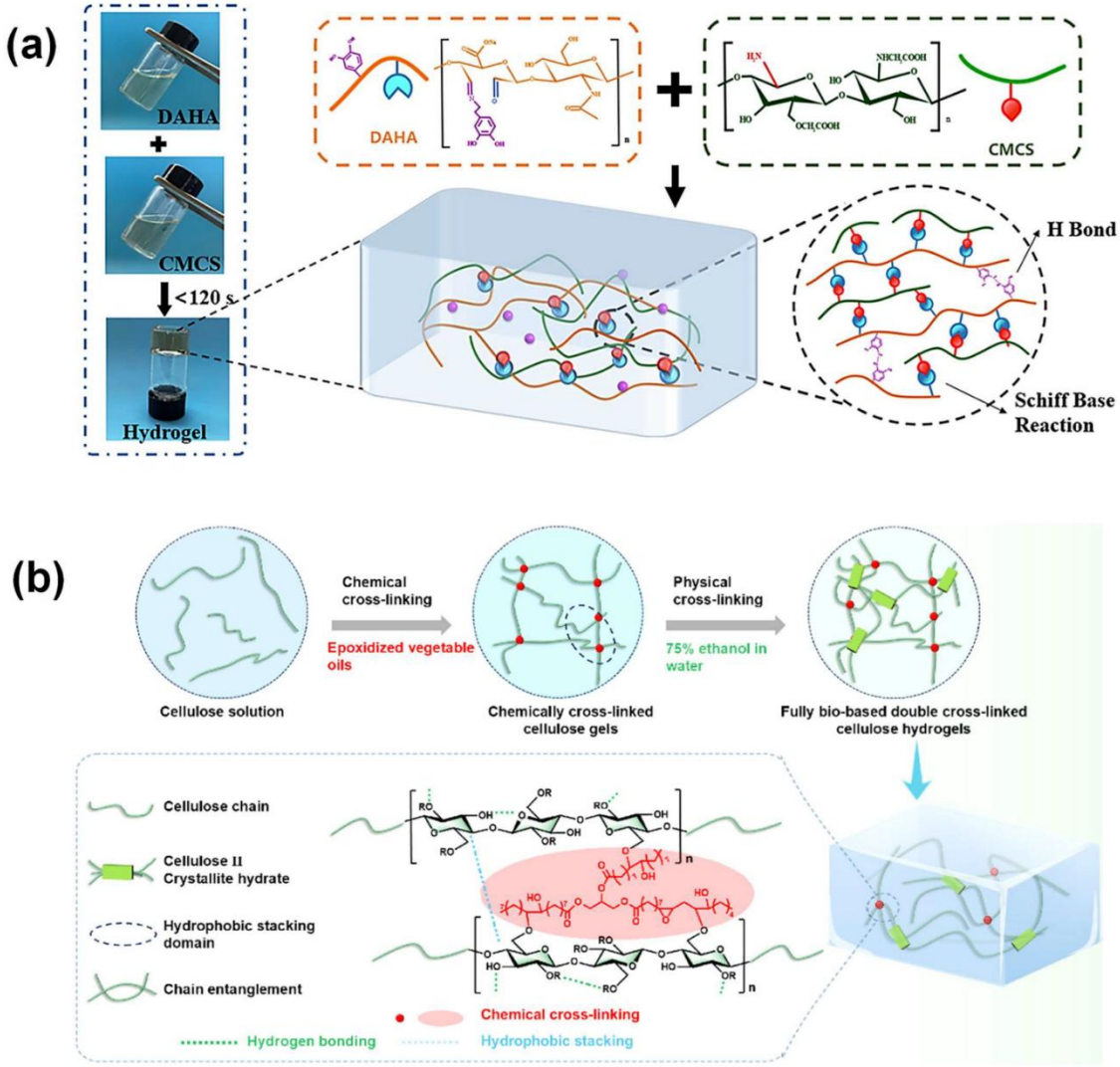

Fig. 2 (a) Crosslinking process of DAHA and CMC solution to form DACS hydrogels (Reproduced with permission from Wang et al. [32]) . (b) Schematic diagram of the preparation process of FBDC cellulose hydrogels (Reproduced with permission from Pan et al. [33]).

2.2. Urgency of hydrogels in agricultural applications

The escalating challenges confronting modern agriculture primarily driven by the dual pressures of climate change and rapid resource depletion have positioned biopolymer-based hydrogels as indispensable tools for global sustainable development. These functional materials address critical bottlenecks in food production by acting as 'miniature reservoirs' within the soil matrix, which significantly enhances irrigation efficiency and mitigates the severe impacts of water scarcity. By increasing the soil's water-holding capacity, hydrogels effectively minimize losses attributed to deep percolation, evaporation, and surface runoff, ensuring that limited freshwater resources are utilized with maximum efficacy[34]. This capability is particularly

vital for climate resilience and drought mitigation; by maintaining a consistent hydration zone around the rhizosphere, hydrogels facilitate a gradual release of moisture to the root system during dry spells, thereby preventing permanent wilting point stress and safeguarding crop yields under adverse conditions. Beyond water management, these polymers function as advanced soil conditioners that promote structural restoration by improving porosity, aeration, and the stabilization of soil aggregates. Such mechanical improvements reduce erosion rates and enhance nutrient availability, protecting the long-term fertility of arable land. From a sustainability perspective, the integration of hydrogels aligns with circular economy objectives by reducing the over-application of fertilizers and preventing the leaching of agrochemicals into groundwater, thus bridging the gap between agribusiness productivity and environmental stewardship. Furthermore, the shift toward bio-based hydrogels derived from cellulose, starch, or chitosan ensures a low-risk environmental profile, as their inherent biodegradability prevents the accumulation of microplastics, ultimately fostering a secure and eco-friendly framework for global food security[34].

2.3.Applications in Lithium-Ion Batteries

Hydrogels have emerged as transformative materials in lithium-ion battery research, addressing critical challenges through their unique three-dimensional networks that facilitate ion transport, accommodate volume changes, and serve as precursors for advanced carbon architectures [35], [36]. For silicon anodes suffering from 300% volume expansion during cycling, hydrogel-based approaches have proven particularly effective[37]. Fibrin hydrogels enable uniform dispersion of silicon nanoparticles within nitrogen-doped carbon matrices, producing 3D Si@C electrodes that deliver 1090 mAh g^{-1} at 100 mA g^{-1} and maintain 725 mAh g^{-1} even at 1000 mA g^{-1} [38]. Hydrogel binders further enhance performance, with chitosan-GA systems achieving 2782 mAh g^{-1} initial capacity [39], hierarchical conducting polymer frameworks retaining over 90% capacity after 5000 cycles[40] , and self-healing tapioca-PAA binders enabling SiO anodes to deliver 901.2 mAh g^{-1} over 1200 cycles [41]. As electrolytes, hydrogels offer improved safety by replacing flammable organic solvents [42], [43], with thermoresponsive smart separators blocking ion transport at elevated temperatures, flame-retardant boron nitride aerogel separators exhibiting minimal degradation, and all-hydrogel coaxial fiber batteries maintaining performance under deformation for wearable applications [44].

Under extreme conditions, polyacrylic acid hydrogels with strong polymer-water interactions maintain high conductivity at −20°C by disrupting ice formation [45], while dual-salt ZL-PAAm systems enable reliable low-temperature operation [46]. As solid-state templates, hydrogels enable 3D nanostructured LLTO frameworks and interconnected LLZO garnets with excellent ionic conductivity [47]. Current trends focus on self-healing, stretchable systems, with freestanding hydrogel electrolyte films stretching 300% while retaining capacity and crumpled nanowire-hydrogel composites maintaining performance after repeated strain [48]. These innovations position hydrogels as key enablers for next-generation lithium-ion batteries in electric vehicles, portable electronics, and grid storage applications[42, 43, 49] , despite ongoing challenges in long-term mechanical stability and production scalability being addressed through nanoparticle reinforcement and interfacial engineering [50, 51, 52, 53].

3. Biochar

Biochar is a fine-pored carbonaceous material produced by the thermal decomposition of biomass, such as plant and agricultural residues, in an environment with little or no oxygen a process known as pyrolysis. It is distinguished by its chemical and biological stability, making it resistant to microbial degradation and capable of remaining in the soil for extended periods without losing its properties. Biochar is primarily used as a soil amendment, enhancing the soil's capacity to retain water and nutrients while improving its structure, which contributes to increased agricultural productivity. Furthermore, it plays a vital role in carbon sequestration, thereby reducing greenhouse gas emissions. This makes it an effective tool in sustainable development strategies and the restoration of degraded lands. Additionally, it can be utilized in water treatment and improving the characteristics of organic matter in the soil, promoting ecological balance and the sustainability of agricultural systems[54, 55].

3.1. Biochar Production

Biochar can be synthesized from materials with high carbon content, including animal manure, agricultural residues, forest waste, industrial bio-waste, plastic waste, microalgae, waste tires, dewatered sludge, and marine and aquatic organisms. Production methods include[56, 57]:

3.1.1.Pyrolysis

Biochar is produced through a process called pyrolysis or thermal decomposition, where biomass is heated in the partial or total absence of oxygen at high temperatures ranging from 300-700°C. This process leaves a solid residue with high carbon content (approximately 70% to 80%).

3.1.2. Gasification

This process converts carbon compounds into gaseous by-products. In the presence of carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), hydrogen (H_2), and gasifying agents such as oxygen, air, and steam, H_2 gas is produced at high temperatures with trace hydrocarbons.

*3.1.*3.Torrefaction

Torrefaction is a relatively new method for biochar production, referred to as mild pyrolysis due to its low heating rate. It occurs in an inert anaerobic environment at a temperature of 300°C, where multiple decomposition mechanisms remove oxygen, moisture, and CO_2 from the biomass. This process alters biomass characteristics, including particle size, moisture content, surface area, heating rate, and energy density.

3.1.4.Hydrothermal Carbonization

Hot water carbonization can produce biochar at temperatures between 180 and 250°C. This is a cost-effective method, and to distinguish it from products generated via dry methods like pyrolysis and gasification, the products of hydrothermal processes are called "hydrochars".

3.2.Biochar Activation

Biochar activation is a fundamental step in making it beneficial for the soil. This involves enriching it with microorganisms, organic matter (such as compost or manure), or nutrients (mineral fertilizers), depending on agricultural needs, soil type, and climate.The activation process leads to the temporary absorption and immobilization of nutrients and available water in the soil. This process can take anywhere from 3 months to a year or more, depending on the presence of microorganisms in the soil. During this period, soil efficiency may decrease due to a deficiency in beneficial microorganisms, which can impact crop yields. There are various activation methods, such as integrating organic fertilizers (compost, manure, and sludge) or mineral fertilizers, especially nitrogen-based ones. It is essential to understand how these products optimize the absorption capacity of biochar and to select the most suitable ones[57], [58].

3.3.Biochar Applications

Biochar acts as a catalyst in a wide range of fields, including agriculture, the environment, and energy. Its properties, particularly its large surface area, make it effective as a catalyst due to its diverse functional groups. For example, O-H groups aid in the uptake of norfloxacin, while C=O and OH- groups are suitable for the uptake of ammonium[59, 60].

Inefficient agricultural land management systems have led to increased carbon dioxide emissions and the degradation of organic compounds in the soil. Extensive research has been conducted to increase the organic carbon content in the soil by incorporating biomass and animal manure. Applying biochar to the soil helps sequester carbon and improve soil quality by neutralizing acidity, increasing cation exchange capacity, and promoting the growth of microorganisms.

Biochar works to: improve soil fertility and increase cation exchange capacity, reduce aluminum toxicity, and support carbon sequestration. It also improves productivity by conserving water and enhancing microbial activity. In addition, biochar is used to treat soil contaminated with toxic pollutants such as heavy metals and pesticides. Biochar produced at high temperatures remains in the soil for a longer period. However, despite its benefits, its properties must be improved before use to avoid any negative effects on plants[61, 62].

4. Bio-based plastics

Bio-based plastics, often referred to simply as bioplastics, have been in use for several decades. In their early stages, these materials were primarily synthetic polymers derived from natural sources such as starch and cellulose. With advancements in technology and economic growth, the category of bioplastics has broadened considerably. In contemporary terms,

bioplastics typically refer to plastics manufactured from biopolymers, which include bio-based polyethylene terephthalate (Bio-PET) and bio-based polyethylene (bio-PE) [63]. More precisely, these materials are defined as those composed of at least 20% carbon derived from renewable biological sources such as crops, algae, and agricultural waste. These materials may be biodegradable or non-biodegradable, for example, biopolyethylene shares the same non-biodegradable properties as its conventional counterpart derived from fossil fuels. Among biodegradable bioplastics are those derived from starch, cellulose, chitosan, hemicellulose, lignin, lipids, and proteins. Furthermore, certain bioplastics like bio-PLA, bio-based polyhydroxyalkanoate (bio-PHA) including polyhydroxybutyrate (PHB) and polyhydroxybutyrate-co-hydroxyvalerate (PHBV) as well as bio-based polypropylene carbonate (bio-PPC) and bio-based polybutylene succinate (bio-PBS), are capable of biodegrading under specific environmental conditions. Conversely, a range of bio-based plastics are not biodegradable, despite their renewable origins. These include bio-PET, bio-based polyethylene furanoate (bio-PEF), bio-based polytrimethylene terephthalate (bio-PTT), bio-based polypropylene (bio-PP), bio-based poly-furfuryl alcohols (bio-PFA), and bio-based polyamide (bio-PA). Bio-based polyurethane (bio-PUR) presents a more nuanced case: while some modified versions of PUR may be biodegradable, conventional bio-PUR typically are not.

4.1. Major types of bio-based plastics

Natural polymers utilized in plastic production are sourced from a range of organisms, encompassing both animals and plants. These polymers can be obtained from lipids and polysaccharides harvested from living organisms, including substances like waxes and alginates. Additionally, proteins such as those derived from peas and wheat, which are plant-based, fall within this category. Lignin represents another significant polymer sourced from plants. Moreover, polyhydroxyalkanoates (PHAs) constitute a key group of polymers in the manufacturing of bioplastics.

4.1.1. Lipid-based plastics

Lipid-based bioplastics are derived from plant oils, such as linseed oil and myrcene, with the choice of oil influencing their composition and physical attributes. These materials exhibit strong water resistance and high tensile strength, rendering them appropriate for uses that demand both robustness and pliability, for instance in food packaging and automotive components [64]. Plastics based on lipids, like polyester amides synthesized from plant oils, are highly amenable to recycling and can be sustainably processed through diverse recycling techniques. They are also recognized for their resistance to chemicals and their flexibility, which contributes to their adaptability in various industrial settings [65].

4.1.2. Polysaccharide-based plastics

Polysaccharide-based plastics, which include materials like starch, cellulose, and polysaccharides from seaweed, capitalize on the abundance and adaptability of natural polymers to provide sustainable alternatives to conventional plastics. Starch-based plastics rank among the earliest and most prevalent forms of bioplastics. They are produced from natural

starch, found abundantly in crops such as corn and potatoes. The characteristics of these plastics are often linked to the ratio of amylose (straight-chain starch) to amylopectin (branched-chain starch) in the raw material; a greater proportion of amylose generally leads to enhanced tensile strength [66]. Such plastics are frequently employed in packaging and single-use products. Examples include thermoplastic starch, valued for its biodegradability, and starch-based blends, where starch is combined with other polymers to enhance flexibility and durability.

Cellulose-based plastics, which are derived from plant fibers, constitute a major class of bioplastics. As one of the most plentiful organic substances on the planet, cellulose is frequently utilized to manufacture films and fibers for a broad spectrum of uses, such as packaging, textiles, and protective coatings. These plastics can be produced from diverse raw material sources, including waste paper. Research by Liu et al. [67] has shown that cellulosic bioplastic films created from various types of discarded paper possess properties like smoothness. On their own, pure cellulosic plastics tend to deform when exposed to moisture. Nevertheless, when incorporated as additives in combination with other substances especially through interactions with polysaccharides they can significantly improve the mechanical properties of the resulting composite materials[68] .

4.1.3. Biologically synthesized polymers

Biologically synthesized polymers represent a class of bioplastics generated through biological mechanisms, primarily involving microbial fermentation and biosynthesis within cells[69] . For instance, Lactobacillus species can produce lactic acid via fermentation using various carbon sources, offering a more economical feedstock for biopolymer synthesis. Polyhydroxyalkanoates (PHAs) are generated in numerous Gram-negative bacteria, with polyhydroxybutyrate (PHB) being produced as a copolymer during the synthesis of short-chain-length PHAs. Significantly, these polymers are biodegradable, ultimately contributing to a reduction in long-term plastic accumulation. Their adaptable mechanical characteristics enable their use across a broad spectrum of applications from packaging and disposable goods to medical and agricultural products[69]. They are also compatible with conventional plastic processing techniques, like injection molding and extrusion, facilitating their integration into existing manufacturing frameworks.

Notwithstanding the advancements achieved, several challenges persist. For example, polylactic acid (PLA) tends to degrade slowly in natural environments and exhibits low crystallinity [70]. PHAs necessitate controlled conditions for effective degradation, a process influenced by factors like their crystallinity and molecular configuration. Regarding UV resistance, PHAs are more effective at blocking ultraviolet radiation, whereas PLA becomes brittle upon extended exposure to sunlight and undergoes more rapid deterioration [71].

4.1.4. Chemically modified bio-based polymers

Among chemically synthesized bio-based polymers is polyethylene furanoate (PEF), manufactured from bio-derived monomers like furandicarboxylic acid and bio-monoethylene glycol. Its synthesis involves methods such as polymerization and polycondensation; however, the former offers distinct benefits, including higher reaction conversions (exceeding 95%), the production of high-molecular-weight PEF ideal for bottle manufacturing, and reduced

discoloration. Specifically, ring-opening polymerization shortens processing times, provides greater control over polymer characteristics, and lowers impurity levels, establishing it as a more efficient and effective route for producing premium-quality PEF [72]. PEF materials are characterized by their brittleness and high ductility. They demonstrate exceptional barrier properties against both oxygen and carbon dioxide, positioning them as outstanding candidates for bottle production [73].

4.1.5. Protein-based plastics

The raw materials for protein-based plastics encompass plant proteins, casein, and other sources [74]. Specifically, soy protein isolate, derived from soy products, is economical, possesses excellent film-forming abilities, and is well-suited for bioplastic production.The primary limitations of protein-based plastics lie in their water resistance and mechanical strength. In recent years, research has focused on enhancing these properties by incorporating active green compounds, such as phenolic additives and stearic acid [75].

4.2.Applications of Bioplastics

With their evolving properties and optimized production methods, bioplastics are increasingly being integrated into diverse applications. Their inherent flexibility allows for use across multiple sectors, offering both environmental and functional advantages.

4.2.1. Packaging Industry

As one of the largest consumers of plastic materials, the packaging industry is under increasing scrutiny regarding its environmental impact, driving a significant shift toward bioplastics as a more sustainable alternative. Derived from renewable resources such as corn, sugarcane, and agricultural waste bioplastics offer a lower carbon footprint, reduced dependency on fossil fuels, and enhanced end-of-life disposal options, including biodegradability, compostability, and recyclability.

In packaging applications, bioplastics such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA) are increasingly utilized in single-use products, including rigid and flexible food containers, films, and wraps. This growing adoption is attributed not only to their reduced environmental impact and degradability under specific conditions but also to their functional properties, such as sufficient mechanical strength, lightweight nature, printability, and optical transparency. These characteristics enable manufacturers to maintain product integrity and shelf appeal while responding to consumer demand and regulatory pressures for more eco-friendly packaging solutions [77 ,76]**.**

4.2.2. Healthcare Sector

The healthcare sector is witnessing a growing adoption of bioplastics across various applications, driven by their biodegradability, biocompatitbility, and functional versatility. Among their most prominent uses are biodegradable sutures and surgical meshes, which eliminate the need for secondary removal procedures and reduce the risk of long-term

complications, thanks to their safe degradation within the body without leaving toxic residues [78].

In pharmaceutical applications, bioplastics are employed in controlled drug delivery systems. These bio-absorbable devices enable the sustained and targeted release of therapeutic agents, such as antibiotics, thereby improving patient compliance, reducing dosing frequency, and enhancing overall treatment efficacy [79]**.** Furthermore, in tissue engineering and regenerative medicine, bioplastics such as polylactic acid (PLA) and polycaprolactone (PCL) are used to fabricate porous scaffolds that temporarily support cell adhesion, proliferation, and tissue formation. These scaffolds degrade at a tunable rate and are gradually resorbed as the native tissue regenerates [79].

Additionally, advanced wound dressings made from bioplastics feature antimicrobial properties, optimal moisture balance, and oxygen permeability, creating a favorable environment for accelerated healing and infection control. Collectively, these innovations underscore the transformative potential of bioplastics in modern, sustainable, and patient-centered healthcare solutions [80].

4.*2.3. Aerospace*

The aerospace industry is undergoing a paradigm shift towards sustainability, increasingly integrating bioplastics into a domain traditionally dominated by high-performance synthetic composites and aluminum alloys. This transition is primarily catalyzed by the urgent need for weight reduction to enhance fuel efficiency and the industry's commitment to circular economy principles. Major stakeholders, including Airbus, Boeing, and NASA, are actively pioneering the use of bio-based polymers, such as Polylactic Acid (PLA) and microalgae-derived bioplastics, for non-primary structural components. For instance, PLA is being extensively tested for 3D-printed cabin interiors, seatback shells, and meal trays due to its significant density advantage (1.3 g/cm^3 compared to 2.5 g/cm^3 for aluminum), which facilitates substantial weight savings and reduced carbon emissions during the production phase. Moreover, innovative research into microalgal biomass has demonstrated that harvested post-contaminant removal residues can be valorized into high-value biopolymers and Sustainable Aviation Fuel (SAF), illustrating a multi-functional approach to aerospace waste management[81, 82] **.**

Despite their environmental benefits, the widespread adoption of bioplastics in primary load-bearing structures remains limited by their inherent mechanical and thermal constraints. Comparative data indicates that while traditional carbon-fiber composites exhibit superior tensile strength (up to 4140 MPa), bioplastics currently range between 160–3000 MPa, making them more suitable for secondary applications like thermal and acoustic insulation or interior panels. To bridge this performance gap, current research is focusing on bio-composites reinforced with natural fibers such as flax or hemp, which offer enhanced mechanical properties and favorable strength-to-weight ratios[83]. Furthermore, material scientists are prioritizing the improvement of flame retardancy and thermal stability to meet the stringent aerospace safety standards (e.g., resistance to extreme temperatures and mechanical stresses). The integration of these biodegradable materials not only reduces reliance on fossil fuels but also offers superior

end-of-life disposal options, such as industrial composting, thereby mitigating the environmental footprint of future aircraft designs[84] .

5. Conclusion

Converting agricultural waste into biopolymer hydrogels, biochar, and bioplastics is one of the most promising strategies for transitioning to a low-carbon, circular bioeconomy. These three materials offer complementary functions: hydrogels contribute to dynamic water and nutrient management, biochar provides sustainable carbon sequestration and absorption, and bioplastics reduce reliance on fossil fuel-derived polymers in the packaging, healthcare, and technology sectors. However, several significant obstacles remain. Hydrogel research is still largely focused on biomedical applications, while agricultural and battery applications are relatively less developed. Biochar activation processes are time-consuming and can sometimes reduce soil fertility in the short term. Bioplastics often suffer from poor mechanical properties, slow degradation under ambient conditions, and higher production costs compared to conventional plastics. Therefore, scalability, regional diversity of raw materials, energy balance throughout the lifecycle, and economic competitiveness require intensive attention.

Future efforts should prioritize integrated biorefinery approaches that produce multiple biomaterials from the same biomass source, utilize waste-derived fillers/enhancers across various material classes, and incorporate rigorous technical, economic, and life-cycle assessments. Strengthening policy incentives, improving linkages between farmers and industry, and investing in regional pilot facilities are also crucial for accelerating practical implementation.

Funding

This research received no external funding.

Ethical Statement

This research does not contain any studies with human or animal subjects performed by any of the authors.

Data Availability Statement

Not Applicable.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] M. Lackner and M. Besharati, “Agricultural Waste: Challenges and Solutions, a Review,” *Waste*, vol. 3, no. 2, p. 18, Jun. 2025, doi: 10.3390/waste3020018.

[2] S. A. Razzak *et al.*, “Biomass-derived carbon materials as sustainable platforms for advanced biomedical applications,” *Environmental Surfaces and Interfaces*, vol. 4, pp. 45–70, Dec. 2026, doi: 10.1016/j.esi.2025.12.004.

[3] F. Kamran, H. Afshar, and F. Shahi, “Recent Advances and Applications of Sustainable and Recyclable Polymers,” *Polym. Eng. Sci.*, vol. 65, no. 8, pp. 3845–3879, Aug. 2025, doi: 10.1002/pen.27257.

[4] B. P. Almeida *et al.*, “Agricultural Biomass as a Resource for Biomaterials, Biofertilizers, and Bioproducts: A Systematic Review,” *Agrochemicals*, vol. 4, no. 4, p. 23, Dec. 2025, doi: 10.3390/agrochemicals4040023.

[5] A. Mahmood, D. Patel, B. Hickson, J. DesRochers, and X. Hu, “Recent Progress in Biopolymer-Based Hydrogel Materials for Biomedical Applications,” *Int. J. Mol. Sci.*, vol. 23, no. 3, p. 1415, Jan. 2022, doi: 10.3390/ijms23031415.

[6] M. Melikoglu, "Advancements in biopolymer production: A review of sustainable approaches and applications," *Next Materials*, vol. 10, p. 101513, Jan. 2026, doi: 10.1016/j.nxmate.2025.101513.
[7] M. Afshar and S. Mofatteh, "Biochar for a sustainable future: Environmentally friendly production and diverse applications," *Results in Engineering*, vol. 23, p. 102433, Sep. 2024, doi: 10.1016/j.rineng.2024.102433.
[8] S. Huang, Q. Dong, S. Che, R. Li, and K. H. D. Tang, "Bioplastics and biodegradable plastics: A review of recent advances, feasibility and cleaner production," *Science of The Total Environment*, vol. 969, p. 178911, Mar. 2025, doi: 10.1016/j.scitotenv.2025.178911.
[9] M. Santhamoorthy *et al.*, "Amidoxime functionalized mesoporous silica nanoparticles for pH-responsive delivery of anticancer drug," *Zeitschrift für Physikalische Chemie*, vol. 238, no. 11, pp. 2135–2146, Nov. 2024, doi: 10.1515/zpch-2023-0488.
[10] K. Thirupathi *et al.*, "Thermosensitive Polymer-Modified Mesoporous Silica for pH and Temperature-Responsive Drug Delivery," *Pharmaceutics*, vol. 15, no. 3, p. 795, Feb. 2023, doi: 10.3390/pharmaceutics15030795.
[11] K. M. Blevins, R. M. Danilkowicz, A. N. Fletcher, N. B. Allen, L. G. Johnson, and S. B. Adams, "In Situ 3D Bioprinting of Musculoskeletal Tissues in Orthopedic Surgery," *J. 3D Print. Med.*, vol. 6, no. 1, pp. 25–36, Mar. 2022, doi: 10.2217/3dp-2021-0022.
[12] A. Basanth, N. Mayilswamy, and B. Kandasubramanian, "Bone regeneration by biodegradable polymers," *Polymer-Plastics Technology and Materials*, vol. 61, no. 8, pp. 816–845, May 2022, doi: 10.1080/25740881.2022.2029886.
[13] M. Santhamoorthy *et al.*, "Preparation of Magnetic Iron Oxide Incorporated Mesoporous Silica Hybrid Composites for pH and Temperature-Sensitive Drug Delivery," *Magnetochemistry*, vol. 9, no. 3, p. 81, Mar. 2023, doi: 10.3390/magnetochemistry9030081.
[14] P. Wang, Z. Luo, and Z. Xiao, "Preparation, physicochemical characterization and in vitro release behavior of resveratrol-loaded oxidized gellan gum/resistant starch hydrogel beads," *Carbohydr. Polym.*, vol. 260, p. 117794, May 2021, doi: 10.1016/j.carbpol.2021.117794.
[15] L. Liu, W. Yao, X. Xie, J. Gao, and X. Lu, "pH-sensitive dual drug loaded janus nanoparticles by oral delivery for multimodal analgesia," *J. Nanobiotechnology*, vol. 19, no. 1, p. 235, Dec. 2021, doi: 10.1186/s12951-021-00974-6.
[16] A. Mohan, M. Santhamoorthy, T. T. V. Phan, and S.-C. Kim, "pNIPAm-Based pH and Thermoresponsive Copolymer Hydrogel for Hydrophobic and Hydrophilic Drug Delivery," *Gels*, vol. 10, no. 3, p. 184, Mar. 2024, doi: 10.3390/gels10030184.
[17] J. H. Ryu, Y. Lee, W. H. Kong, T. G. Kim, T. G. Park, and H. Lee, "Catechol-Functionalized Chitosan/Pluronic Hydrogels for Tissue Adhesives and Hemostatic Materials," *Biomacromolecules*, vol. 12, no. 7, pp. 2653–2659, Jul. 2011, doi: 10.1021/bm200464x.
[18] X. Pan *et al.*, "Preparation, characterisation and comparison of glabridin-loaded hydrogel-forming microneedles by chemical and physical cross-linking," *Int. J. Pharm.*, vol. 617, p. 121612, Apr. 2022, doi: 10.1016/j.ijpharm.2022.121612.
[19] S. S. Sana *et al.*, "Recent advances on MXene-based hydrogels for antibacterial and drug delivery applications," *Process Biochemistry*, vol. 132, pp. 200–220, Sep. 2023, doi: 10.1016/j.procbio.2023.06.022.
[20] H. Zhang, X. Sun, M. Hubbe, and L. Pal, "Flexible and Pressure-Responsive Sensors from Cellulose Fibers Coated with Multiwalled Carbon Nanotubes," *ACS Appl. Electron. Mater.*, vol. 1, no. 7, pp. 1179–1188, Jul. 2019, doi: 10.1021/acsaelm.9b00182.
[21] M. Santhamoorthy *et al.*, "L-lysine Functionalized Mesoporous Silica Hybrid Nanoparticles for pH-Responsive Delivery of Curcumin," *Pharmaceutics*, vol. 15, no. 6, p. 1631, May 2023, doi: 10.3390/pharmaceutics15061631.
[22] T. T. V. Phan and M. Santhamoorthy, "Preparation of Dual pH- and Temperature-Sensitive Nanogels for Curcumin Delivery," in *IOCN 2023*, Basel Switzerland: MDPI, May 2023, p. 71. doi: 10.3390/IOCN2023-14468.
[23] E. Barrett-Catton, M. L. Ross, and P. Asuri, "Multifunctional Hydrogel Nanocomposites for Biomedical Applications," *Polymers (Basel).*, vol. 13, no. 6, p. 856, Mar. 2021, doi: 10.3390/polym13060856.

[24] M. Santhamoorthy *et al.*, "L-Lysine-Modified pNIPAm-co-GMA Copolymer Hydrogel for pH- and Temperature-Responsive Drug Delivery and Fluorescence Imaging Applications," *Gels*, vol. 9, no. 5, p. 363, Apr. 2023, doi: 10.3390/gels9050363.

[25] J. Zhang *et al.*, "Optimization of mechanical stiffness and cell density of 3D bioprinted cell-laden scaffolds improves extracellular matrix mineralization and cellular organization for bone tissue engineering," *Acta Biomater.*, vol. 114, pp. 307–322, Sep. 2020, doi: 10.1016/j.actbio.2020.07.016.

[26] S. Lee, H. S. Kim, and H. S. Yoo, "Electrospun nanofibrils embedded hydrogel composites for cell cultivation in a biomimetic environment," *RSC Adv.*, vol. 7, no. 85, pp. 54246–54253, 2017, doi: 10.1039/C7RA08595H.

[27] X. Wei, Y. Luo, and P. Huang, "3D bioprinting of alginate scaffolds with controlled micropores by leaching of recrystallized salts," *Polymer Bulletin*, vol. 76, no. 12, pp. 6077–6088, Dec. 2019, doi: 10.1007/s00289-019-02690-6.

[28] J. Zhang *et al.*, "Optimization of mechanical stiffness and cell density of 3D bioprinted cell-laden scaffolds improves extracellular matrix mineralization and cellular organization for bone tissue engineering," *Acta Biomater.*, vol. 114, pp. 307–322, Sep. 2020, doi: 10.1016/j.actbio.2020.07.016.

[29] O. Yom-Tov, D. Seliktar, and H. Bianco-Peled, "PEG-Thiol based hydrogels with controllable properties," *Eur. Polym. J.*, vol. 74, pp. 1–12, Jan. 2016, doi: 10.1016/j.eurpolymj.2015.11.002.

[30] M. S. Moorthy, P. K. Tapaswi, S. S. Park, A. Mathew, H.-J. Cho, and C.-S. Ha, "Ion-imprinted mesoporous silica hybrids for selective recognition of target metal ions," *Microporous and Mesoporous Materials*, vol. 180, pp. 162–171, Nov. 2013, doi: 10.1016/j.micromeso.2013.06.010.

[31] M. Santhamoorthy and S.-C. Kim, "Dual pH- and Thermo-Sensitive Poly(N-isopropylacrylamide-co-allylamine) Nanogels for Curcumin Delivery: Swelling–Deswelling Behavior and Phase Transition Mechanism," *Gels*, vol. 9, no. 7, p. 536, Jul. 2023, doi: 10.3390/gels9070536.

[32] R. Wang *et al.*, "Dynamic Crosslinked Injectable Mussel-Inspired Hydrogels with Adhesive, Self-Healing, and Biodegradation Properties," *Polymers (Basel).*, vol. 15, no. 8, p. 1876, Apr. 2023, doi: 10.3390/polym15081876.

[33] H. Pan *et al.*, "Fully Biobased High-Strength and High-Toughness Double Cross-Linked Cellulose Hydrogel for Flexible Electrolytes," *ACS Sustain. Chem. Eng.*, vol. 12, no. 50, pp. 18231–18244, Dec. 2024, doi: 10.1021/acssuschemeng.4c07758.

[34] Z. Tariq, D. N. Iqbal, M. Rizwan, M. Ahmad, M. Faheem, and M. Ahmed, "Significance of biopolymer-based hydrogels and their applications in agriculture: a review in perspective of synthesis and their degree of swelling for water holding," *RSC Adv.*, vol. 13, no. 35, pp. 24731–24754, 2023, doi: 10.1039/D3RA03472K.

[35] Y. Guo, J. Bae, F. Zhao, and G. Yu, "Functional hydrogels for next-generation batteries and supercapacitors," *Trends Chem.*, vol. 1, no. 3, pp. 335–348, 2019.

[36] C. Lu and X. Chen, "All-temperature flexible supercapacitors enabled by antifreezing and thermally stable hydrogel electrolyte," *Nano Lett.*, vol. 20, no. 3, pp. 1907–1914, 2020.

[37] F. Zou and A. Manthiram, "A review of the design of advanced binders for high-performance batteries," *Adv. Energy Mater.*, vol. 10, no. 45, p. 2002508, 2020.

[38] W.-J. Kim, J. G. Kang, and D.-W. Kim, "Fibrin biopolymer hydrogel-templated 3D interconnected Si@ C framework for lithium ion battery anodes," *Appl. Surf. Sci.*, vol. 551, p. 149439, 2021.

[39] C. Chen, S. H. Lee, M. Cho, J. Kim, and Y. Lee, "Cross-linked chitosan as an efficient binder for Si anode of Li-ion batteries," *ACS Appl. Mater. Interfaces*, vol. 8, no. 4, pp. 2658–2665, 2016.

[40] X. Liu *et al.*, "Rational design of stretchable and conductive hydrogel binder for highly reversible SiP2 anode," *Journal of Energy Chemistry*, vol. 83, pp. 564–573, 2023.

[41] W. Wang *et al.*, "Novel-designed cobweb-like binder by 'four-in-one' strategy for high performance SiO anode," *Chemical Engineering Journal*, vol. 458, p. 141387, 2023.

[42] J. Liu, C. Yang, X. Chi, B. Wen, W. Wang, and Y. Liu, "Water/sulfolane hybrid electrolyte achieves ultralow-temperature operation for high-voltage aqueous lithium-ion batteries," *Adv. Funct. Mater.*, vol. 32, no. 1, p. 2106811, 2022.

[43] L. Ma *et al.*, "Super-stretchable zinc–air batteries based on an alkaline-tolerant dual-network hydrogel electrolyte," *Adv. Energy Mater.*, vol. 9, no. 12, p. 1803046, 2019.
[44] J. Wang *et al.*, "Ultrasoft all-hydrogel aqueous lithium-ion battery with a coaxial fiber structure," *Polym. J.*, vol. 54, no. 11, pp. 1383–1389, 2022.
[45] Z. Pei *et al.*, "A flexible rechargeable zinc–air battery with excellent low-temperature adaptability," *Angew. Chem. Int. Ed.*, vol. 59, no. 12, pp. 4793–4799, 2020.
[46] M. Zhu *et al.*, "Antifreezing hydrogel with high zinc reversibility for flexible and durable aqueous batteries by cooperative hydrated cations," *Adv. Funct. Mater.*, vol. 30, no. 6, p. 1907218, 2020.
[47] J. Bae *et al.*, "A 3D nanostructured hydrogel-framework-derived high-performance composite polymer lithium-ion electrolyte," *Angew. Chem. Int. Ed.*, vol. 57, no. 8, pp. 2096–2100, 2018.
[48] X. Cao *et al.*, "High-performance fully-stretchable solid-state lithium-ion battery with a nanowire-network configuration and crosslinked hydrogel," *J. Mater. Chem. A Mater.*, vol. 10, no. 21, pp. 11562–11573, 2022.
[49] A. Herrmann, R. Haag, and U. Schedler, "Hydrogels and their role in biosensing applications," *Adv. Healthc. Mater.*, vol. 10, no. 11, p. 2100062, 2021.
[50] Z. Shen, J. Huang, Y. Xie, D. Wei, J. Chen, and Z. Shi, "Solid electrolyte interphase on lithium metal anodes," *ChemSusChem*, vol. 17, no. 11, p. e202301777, 2024.
[51] M. Zhao, B.-Q. Li, X.-Q. Zhang, J.-Q. Huang, and Q. Zhang, "A perspective toward practical lithium–sulfur batteries," *ACS Cent. Sci.*, vol. 6, no. 7, pp. 1095–1104, 2020.
[52] F. Zou and A. Manthiram, "A review of the design of advanced binders for high-performance batteries," *Adv. Energy Mater.*, vol. 10, no. 45, p. 2002508, 2020.
[53] A. S. Kulathuvayal and Y. Su, "Ionic transport through the solid electrolyte interphase in lithium-ion batteries: A review from first-principles perspectives," *ACS Appl. Energy Mater.*, vol. 6, no. 11, pp. 5628–5645, 2023.
[54] A. A. Boateng, M. Garcia-Perez, O. Mašek, R. Brown, and B. del Campo, "Biochar production technology," in *Biochar for environmental management*, Routledge, 2015, pp. 63–87.
[55] J. Wang and S. Wang, "Preparation, modification and environmental application of biochar: A review," *J. Clean. Prod.*, vol. 227, pp. 1002–1022, 2019.
[56] J. S. Cha *et al.*, "Production and utilization of biochar: A review," *Journal of Industrial and Engineering Chemistry*, vol. 40, pp. 1–15, 2016.
[57] B. Sajjadi, W.-Y. Chen, and N. O. Egiebor, "A comprehensive review on physical activation of biochar for energy and environmental applications," *Reviews in Chemical Engineering*, vol. 35, no. 6, pp. 735–776, 2019.
[58] A. K. Sakhiya, A. Anand, and P. Kaushal, "Production, activation, and applications of biochar in recent times," *Biochar*, vol. 2, no. 3, pp. 253–285, 2020.
[59] K. H. Min, K. H. Kim, J.-H. Seo, and S. P. Pack, "Biochar utilization in antimicrobial, anticancer, and biosensing applications: a review," *Biomolecules*, vol. 15, no. 6, p. 760, 2025.
[60] J. L. Gomez-Eyles, T. Sizmur, C. D. Collins, and M. E. Hodson, "Effects of biochar and the earthworm Eisenia fetida on the bioavailability of polycyclic aromatic hydrocarbons and potentially toxic elements," *Environmental pollution*, vol. 159, no. 2, pp. 616–622, 2011.
[61] Z. Tan, Y. Wang, L. Zhang, and Q. Huang, "Study of the mechanism of remediation of Cd-contaminated soil by novel biochars," *Environmental Science and Pollution Research*, vol. 24, no. 32, pp. 24844–24855, 2017.
[62] M. Ahmad *et al.*, "Effects of pyrolysis temperature on soybean stover-and peanut shell-derived biochar properties and TCE adsorption in water," *Bioresour. Technol.*, vol. 118, pp. 536–544, 2012.
[63] V. Siracusa and I. Blanco, "Bio-Polyethylene (Bio-PE), Bio-Polypropylene (Bio-PP) and Bio-Poly(ethylene terephthalate) (Bio-PET): Recent Developments in Bio-Based Polymers Analogous to Petroleum-Derived Ones for Packaging and Engineering Applications," *Polymers (Basel).*, vol. 12, no. 8, p. 1641, Jul. 2020, doi: 10.3390/polym12081641.
[64] D. C. Rodrigues, A. P. Cunha, E. S. Brito, H. M. C. Azeredo, and M. I. Gallão, "Mesquite seed gum and palm fruit oil emulsion edible films: Influence of oil content and sonication," *Food Hydrocoll.*, vol. 56, pp. 227–235, May 2016, doi: 10.1016/j.foodhyd.2015.12.018.

[65] X. Yang, M. Guo, X. Wang, W. Huan, and M. Li, "Biobased Epoxies Derived from Myrcene and Plant Oil: Design and Properties of Their Cured Products," *ACS Omega*, vol. 5, no. 45, pp. 28918–28928, Nov. 2020, doi: 10.1021/acsomega.0c02166.

[66] M. M. Abe *et al.*, "Advantages and Disadvantages of Bioplastics Production from Starch and Lignocellulosic Components," *Polymers (Basel).*, vol. 13, no. 15, p. 2484, Jul. 2021, doi: 10.3390/polym13152484.

[67] M. Liu, S. Tong, Z. Tong, Y. Guan, and Y. Sun, "A strong, biodegradable and transparent cellulose-based bioplastic stemmed from waste paper," *J. Appl. Polym. Sci.*, vol. 140, no. 13, Apr. 2023, doi: 10.1002/app.53671.

[68] M. M. Abe *et al.*, "Advantages and Disadvantages of Bioplastics Production from Starch and Lignocellulosic Components," *Polymers (Basel).*, vol. 13, no. 15, p. 2484, Jul. 2021, doi: 10.3390/polym13152484.

[69] M. S. da F. Diniz, M. M. Mourão, L. P. Xavier, and A. V. Santos, "Recent Biotechnological Applications of Polyhydroxyalkanoates (PHA) in the Biomedical Sector—A Review," *Polymers (Basel).*, vol. 15, no. 22, p. 4405, Nov. 2023, doi: 10.3390/polym15224405.

[70] J. E. Weinstein, J. L. Dekle, R. R. Leads, and R. A. Hunter, "Degradation of bio-based and biodegradable plastics in a salt marsh habitat: Another potential source of microplastics in coastal waters," *Mar. Pollut. Bull.*, vol. 160, p. 111518, Nov. 2020, doi: 10.1016/j.marpolbul.2020.111518.

[71] M. Koller and A. Mukherjee, "Polyhydroxyalkanoate (PHA) Bio-polyesters – Circular Materials for Sustainable Development and Growth," *Chem. Biochem. Eng. Q.*, no. 4, Feb. 2023, doi: 10.15255/CABEQ.2022.2124.

[72] C. M. Mendieta, G. González, M. E. Vallejos, and M. C. Area, "Bio-polyethylene furanoate (Bio-PEF) from lignocellulosic biomass adapted to the circular bioeconomy," *Bioresources*, vol. 17, no. 4, pp. 7313–7337, Oct. 2022, doi: 10.15376/biores.17.4.Mendieta.

[73] K. Loos *et al.*, "A Perspective on PEF Synthesis, Properties, and End-Life," *Front. Chem.*, vol. 8, Jul. 2020, doi: 10.3389/fchem.2020.00585.

[74] T. Shevtsova *et al.*, "Enhancing Plant Protein-Based Bioplastics with Natural Additives: A Comprehensive Study by Experimental and Computational Approaches," *ACS Sustain. Chem. Eng.*, vol. 12, no. 43, pp. 15948–15960, Oct. 2024, doi: 10.1021/acssuschemeng.4c03971.

[75] Q. Ye, Y. Han, J. Zhang, W. Zhang, C. Xia, and J. Li, "Bio-based films with improved water resistance derived from soy protein isolate and stearic acid via bioconjugation," *J. Clean. Prod.*, vol. 214, pp. 125–131, Mar. 2019, doi: 10.1016/j.jclepro.2018.12.277.

[76] G. Bishop, D. Styles, and P. N. L. Lens, "Environmental performance of bioplastic packaging on fresh food produce: A consequential life cycle assessment," *J. Clean. Prod.*, vol. 317, p. 128377, Oct. 2021, doi: 10.1016/j.jclepro.2021.128377.

[77] S. Kakadellis and Z. M. Harris, "Don't scrap the waste: The need for broader system boundaries in bioplastic food packaging life-cycle assessment – A critical review," *J. Clean. Prod.*, vol. 274, p. 122831, Nov. 2020, doi: 10.1016/j.jclepro.2020.122831.

[78] V. Upadhayay, S. Verma, and A. Kuila, "Production of poly hydroxy butyrate (PHB) from Eichhornia crassipes through microbial fermentation process," *Plant Science Today*, vol. 6, no. sp1, pp. 541–550, Dec. 2019, doi: 10.14719/pst.2019.6.sp1.673.

[79] M. He *et al.*, "Biocompatible and Biodegradable Bioplastics Constructed from Chitin via a 'Green' Pathway for Bone Repair," *ACS Sustain. Chem. Eng.*, vol. 5, no. 10, pp. 9126–9135, Oct. 2017, doi: 10.1021/acssuschemeng.7b02051.

[80] S. Buonvino, M. Ciocci, F. Nanni, I. Cacciotti, and S. Melino, "New vegetable-waste biomaterials by Lupin albus L. as cellular scaffolds for applications in biomedicine and food," *Biomaterials*, vol. 293, p. 121984, Feb. 2023, doi: 10.1016/j.biomaterials.2022.121984.

[81] S. Mehariya *et al.*, "Microalgae: A potential bioagent for treatment of emerging contaminants from domestic wastewater," *Chemosphere*, vol. 351, p. 141245, Mar. 2024, doi: 10.1016/j.chemosphere.2024.141245.

[82] G. Pathinettampadian, M. Vellaisamy, T. Kumar Muthu Kumar, M. Agnelo Browne, and M. Kumar Subramaniyan, "Some studies on functional behavior of novel multi-layered material for integrated structural application," *Journal of Industrial and Engineering Chemistry*, vol. 131, pp. 545–557, Mar. 2024, doi: 10.1016/j.jiec.2023.10.059.

[83] M. Norkhairunnisa, T. Chai Hua, F. Bajuri, I. N. Yaacob, and K. A. Ahmad, "Sustainable Biocomposite-Based Biomass for Aerospace Applications," *Plant Biomass Derived Materials: Sources, Extractions, and Applications*, pp. 517–535, 2024.

[84] O. Olatunji, "Plastics and space exploration," *Re-envisioning Plastics Role in the Global Society: Perspectives on Food, Urbanization, and Environment*, pp. 195–217, 2024.