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CIRCULAR BIOECONOMY AND GREEN EXTRACTION TECHNOLOGIES FOR CELLULOSE RECOVERY FROM FRUIT AND VEGETABLE PEEL WASTE: ADVANCES, CHALLENGES, AND FUTURE PERSPECTIVES

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ABSTRACT
The rapid growth of agro-industrial activities has led to the generation of substantial quantities of fruit and vegetable peel waste, posing serious environmental and disposal challenges. These lignocellulosic residues are rich in cellulose, a renewable, biodegradable, and versatile biopolymer with wide applications in food, pharmaceutical, packaging, textile, and biomedical industries. In recent years, increasing attention has been directed toward the valorization of fruit and vegetable peels as sustainable feedstocks for cellulose extraction, in line with circular economy and waste-to-wealth concepts. This review provides a comprehensive overview of the sources, composition, and structural characteristics of cellulose present in fruit and vegetable peel waste. Various extraction and isolation technologies, including conventional chemical treatments, physical and mechanical processes, enzymatic methods, and emerging green and eco-friendly approaches, are critically discussed. The influence of processing parameters on cellulose yield, purity, crystallinity, and functional properties is examined. Furthermore, the key challenges associated with cellulose extraction-such as high chemical consumption, energy demand, scalability issues, and environmental concerns-are analyzed. Finally, future perspectives focusing on green extraction technologies, biorefinery integration, and advanced applications of peel-derived cellulose are highlighted. This review aims to serve as a valuable reference for researchers and industry stakeholders seeking sustainable strategies for cellulose recovery from fruit and vegetable peel waste.

KEYWORDS: Cellulose extraction; fruit and vegetable peels; agro-industrial waste; green technologies; biopolymer valorization and circular economy.

1. INTRODUCTION

1.1. Importance of Cellulose as a Renewable Biopolymer

Cellulose is the most abundant naturally occurring biopolymer on Earth and constitutes the primary structural component of plant cell walls. It is a linear polysaccharide composed of repeating β-D-glucopyranose units linked through β(1→4) glycosidic bonds, forming long chains that aggregate into microfibrils stabilized by extensive intra- and intermolecular hydrogen bonding (Klemm et al., 2005; Sun, 2012). This unique molecular architecture imparts cellulose with high tensile strength, rigidity, thermal stability, and resistance to chemical degradation, while simultaneously maintaining biodegradability and biocompatibility. These intrinsic properties have made cellulose a cornerstone material across a wide range of industrial sectors, including paper and pulp, textiles, food, pharmaceuticals, construction, and emerging bio-based materials (Fellows, 2009; Klemm et al., 2005). In recent decades, growing environmental concerns related to climate change, plastic pollution, and depletion of fossil resources have intensified global interest in renewable and sustainable materials. In this context, cellulose has emerged as a promising alternative to petroleum-derived polymers due to its renewable origin, low toxicity, carbon neutrality, and end-of-life biodegradability (Sun, 2012; Galanakis, 2020). Moreover, advancements in processing and nanotechnology have enabled the development of cellulose-based derivatives such as microcrystalline cellulose, cellulose nanofibers, and cellulose nanocrystals, which exhibit enhanced mechanical, barrier, and functional properties suitable for high-value applications in packaging, biomedical devices, and advanced composites (Kritzinger et al., 2018; Zhang et al., 2022). Traditionally, industrial cellulose production relies heavily on wood pulp and cotton linters, which provide high cellulose purity but are associated with significant environmental and socio-economic challenges. These include deforestation, intensive water and chemical usage, high energy consumption, and competition with land required for

food production (Sun, 2012; Mirabella et al., 2014). Consequently, the identification of alternative, low-cost, and sustainable cellulose sources has become a critical research priority. Agricultural residues and food processing wastes have gained increasing attention as viable feedstocks for cellulose extraction, offering opportunities to decouple cellulose production from forest-based resources while supporting circular bioeconomy models (Galanakis, 2020; Misra et al., 2020).

1.2. Fruit and Vegetable Peel Waste as an Underutilized Resource

The global food supply chain generates enormous quantities of waste, with fruits and vegetables accounting for a significant share due to their high perishability and extensive processing requirements. During industrial processing and household consumption, large volumes of peels, rinds, skins, pomace, and trimmings are produced, often representing 30–60% of the original raw material depending on the commodity (Mirabella et al., 2014; Galanakis, 2020). Fruit and vegetable peel (FVP) waste is commonly discarded or used in low-value applications such as animal feed, composting, or landfill disposal, despite being rich in structurally valuable biopolymers. From a compositional perspective, fruit and vegetable peels are lignocellulosic in nature and contain appreciable amounts of cellulose, hemicellulose, lignin, pectin, and other polysaccharides, along with minor quantities of proteins, lipids, and phenolic compounds (Fellows, 2009; Badia-Melis et al., 2015). In many cases, the cellulose content of peels is comparable to or even higher than that of some traditional agricultural residues, making them an attractive but underexploited biomass resource (Galanakis, 2020). For example, banana, citrus, mango, pineapple, and potato peels have been reported to possess substantial cellulose fractions suitable for extraction and downstream valorization (Kerry et al., 2006; Realini and Marcos, 2014). The improper disposal of fruit and vegetable peel waste poses serious environmental challenges, including methane emissions from landfills, leachate generation, and loss of potentially valuable materials. At the same time, increasing global food demand and tightening environmental regulations are driving the food industry to adopt sustainable waste management strategies that prioritize resource recovery and value addition (OECD, 2020). In this regard, the valorization of FVP waste for cellulose extraction aligns strongly with circular economy principles by transforming waste streams into high-value renewable materials while reducing environmental burdens (Mirabella et al., 2014; Galanakis, 2020). Recent research has demonstrated that cellulose isolated from fruit and vegetable peels can be successfully utilized in the production of biodegradable films, reinforcement fillers, edible coatings, nanocellulose materials, and functional composites (Realini and Marcos, 2014; Zhang et al., 2024). Such applications not only enhance the economic value of food processing by-products but also contribute to the development of sustainable alternatives to conventional plastics. However, the heterogeneity of peel biomass, variability in composition, and presence of non-cellulosic components present challenges in achieving efficient and consistent cellulose extraction, necessitating systematic investigation and optimization of extraction methodologies.

1.3. Rationale and Objectives of the Review

Although extensive research has been conducted on cellulose extraction from conventional lignocellulosic materials such as wood, straw, and bagasse, comparatively fewer comprehensive reviews focus specifically on fruit and vegetable peel waste as a dedicated cellulose source. Existing literature on FVP waste has largely concentrated on the recovery of bioactive compounds, dietary fibers, and pectin, with limited emphasis on cellulose isolation pathways, structural characterization, and application potential (Kerry et al., 2006; Badia-Melis et al., 2018). Furthermore, studies investigating cellulose extraction from peel waste often employ diverse methodologies, including chemical, physical, enzymatic, and emerging green techniques, making it difficult to draw generalized conclusions regarding process efficiency, scalability, and sustainability. Given the increasing emphasis on waste valorization, renewable materials, and circular bioeconomy frameworks, a consolidated and critical evaluation of cellulose extraction from fruit and vegetable peel waste is timely and necessary. Such a review can help identify best practices, technological gaps, and research priorities while facilitating the translation of laboratory-scale findings into industrially viable processes. Moreover, understanding the influence of peel type, pretreatment strategies, and extraction conditions on cellulose yield and quality is essential for tailoring applications in packaging, composites, and advanced functional materials.

2. Fruit and Vegetable Peel Waste as a Source of Cellulose

Fruit and vegetable peel waste (FVPW) represents a major fraction of agro-industrial and household food waste and has gained increasing attention as a sustainable and low-cost source of cellulose. The abundance, renewability, and lignocellulosic nature of peel residues make them highly suitable for cellulose extraction and valorization within circular bioeconomy frameworks.

2.1. Types and Availability of Fruit and Vegetable Peel Waste

The global production and processing of fruits and vegetables generate enormous quantities of peel waste at different stages of the food supply chain, including post-harvest handling, industrial processing, retail, and domestic consumption. Peels, rinds, skins, and outer layers are typically removed to improve sensory quality, safety, and shelf life, resulting in significant by-product generation. It has been estimated that fruit and vegetable processing industries alone account for nearly 25–40% of total food waste globally, with peel waste constituting a substantial proportion of this volume (Mirabella et al., 2014; Galanakis, 2020). Common fruit peel wastes include banana, orange, lemon, mango, pineapple, apple, and pomegranate peels, while major vegetable peel wastes arise from potato, carrot, onion, beetroot, and cucumber processing (Badia-Melis et al., 2015; Galanakis, 2020). These wastes are often produced in concentrated locations such as juice factories, canning industries, and fresh-cut processing units, making them readily available and logistically feasible feedstocks for biomass valorization. However, despite their availability, peel wastes

are largely underutilized and frequently disposed of through landfilling or low-value applications such as animal feed, leading to environmental and economic losses (Mirabella et al., 2014). From a sustainability perspective, fruit and vegetable peels offer several advantages over conventional lignocellulosic sources. They do not compete with food production, require no additional land or water resources, and contribute to waste reduction when effectively valorized (Galanakis, 2020). Their continuous and seasonal availability further enhances their potential as renewable raw materials for cellulose extraction.

Table 1. Major fruit and vegetable peel wastes and their global availability (Mirabella et al., 2014; Galanakis, 2020)

Peel source	Major producing regions	Typical processing industry	Availability characteristics
Banana peel	Asia, Africa, Latin America	Chips, puree, flour	Year-round, high volume
Citrus peel (orange, lemon)	Mediterranean, Brazil, USA	Juice, concentrate	Seasonal, centralized
Mango peel	India, Southeast Asia	Pulp, nectar	Seasonal, regional
Pineapple peel	Tropical regions	Canning, juice	Seasonal, high moisture
Potato peel	Europe, Asia, North America	Chips, fries, starch	Year-round, industrial
Onion peel	Global	Dehydration, fresh-cut	Year-round, dry biomass

2.2. Chemical Composition and Lignocellulosic Structure

Fruit and vegetable peel wastes are primarily composed of lignocellulosic biomass, consisting of cellulose, hemicellulose, lignin, pectin, and minor components such as proteins, lipids, ash, and phenolic compounds. Among these constituents, cellulose serves as the main structural polysaccharide, forming a rigid network that provides mechanical strength to plant tissues (Klemm et al., 2005; Fellows, 2009). Cellulose in peel biomass exists as semi-crystalline microfibrils embedded in a complex matrix of hemicellulose and lignin. Hemicellulose acts as an amorphous polysaccharide that links cellulose microfibrils, while lignin functions as a hydrophobic, aromatic polymer that provides rigidity and resistance to microbial degradation (Sun, 2012). Pectin is another significant component, particularly in fruit peels, contributing to cell adhesion and water retention (Kerry et al., 2006). The intimate association of cellulose with these components necessitates effective pretreatment and extraction strategies to isolate cellulose with high purity. The relative proportion of cellulose in peel waste varies depending on plant species, maturity, growing conditions, and processing methods. Generally, fruit peels contain lower lignin but higher pectin content compared to vegetable peels, which often exhibit higher cellulose and hemicellulose fractions (Badia-Melis et al., 2018). This compositional diversity influences the choice of extraction techniques and determines the yield and quality of recovered cellulose.

Table 2. Typical lignocellulosic composition of selected fruit and vegetable peels (% dry basis) (Fellows, 2009; Kerry et al., 2006; Badia-Melis et al., 2018; Galanakis, 2020)

Peel type	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Pectin (%)
Banana peel	10–21	8–15	6–12	10–20
Orange peel	9–18	10–16	2–6	20–35
Mango peel	15–25	12–18	5–10	15–25
Pineapple peel	18–30	10–20	4–8	10–18
Potato peel	20–35	15–25	5–15	5–10
Onion peel	25–40	10–20	10–20	3–8

2.3. Variability among Different Fruits and Vegetables

One of the key challenges in utilizing fruit and vegetable peel waste as a cellulose source is the inherent variability in biomass composition. Differences in botanical origin, tissue structure, and biochemical makeup lead to substantial variation in cellulose content and extractability (Galanakis, 2020). For instance, starchy vegetable peels such as potato and carrot generally exhibit higher cellulose content and lower pectin levels, making them more suitable for direct cellulose extraction. In contrast, citrus and apple peels contain high pectin concentrations, requiring additional pretreatment steps to remove non-cellulosic polysaccharides prior to cellulose isolation (Kerry et al., 2006; Realini and Marcos, 2014). Environmental factors such as soil composition, climate, agricultural practices, and maturity at harvest further influence peel composition. Post-harvest processing conditions, including thermal treatment, drying, and mechanical abrasion, can also alter the physicochemical structure of peel biomass and affect cellulose recovery efficiency (Sun, 2012). These variations necessitate feedstock-specific optimization of extraction protocols to achieve consistent cellulose yield and quality. Moreover, the structural arrangement of cellulose microfibrils differs among fruits and vegetables, influencing crystallinity, degree of polymerization, and mechanical properties of extracted cellulose (Klemm et al., 2005). Such differences are particularly important when peel-derived cellulose is intended for advanced applications such as nanocellulose production, biodegradable packaging, or composite reinforcement. Understanding and managing this variability is therefore critical for scaling up peel-based cellulose extraction processes

and ensuring product standardization.

3. Structure and Properties of Cellulose

Cellulose is a linear polysaccharide that serves as the primary structural component of plant cell walls and is the dominant fraction of lignocellulosic biomass. The structure, organization, and physicochemical properties of cellulose strongly influence its behavior during extraction, modification, and final application. Understanding these aspects is essential when valorizing cellulose from fruit and vegetable peel wastes, as variations in molecular structure and supramolecular arrangement directly affect processing efficiency and end-use performance.

3.1. Molecular Structure and Polymorphism of Cellulose

At the molecular level, cellulose is composed of repeating β-D-glucopyranose units linked through β(1→4) glycosidic bonds, forming long, unbranched chains. Each anhydroglucose unit contains three hydroxyl groups at the C2, C3, and C6 positions, which participate in extensive intra- and intermolecular hydrogen bonding. This hydrogen bonding network is responsible for the high rigidity, insolubility in water, and crystalline nature of cellulose (Klemm et al., 2005; Moon et al., 2011). Native cellulose chains aggregate into elementary fibrils, which further assemble into microfibrils embedded within a matrix of hemicellulose, lignin, and pectin in plant tissues. In fruit and vegetable peels, cellulose microfibrils are often less ordered than in wood fibers due to higher pectin content and amorphous polysaccharides, which influences extractability and purity (Sun et al., 2016; Badia-Melis et al., 2015). Cellulose exists in several polymorphic forms, differing in crystalline arrangement and hydrogen bonding patterns. Cellulose I, the native form found in plants, is subdivided into cellulose Iα and Iβ, with Iβ being dominant in higher plants. Chemical treatments such as alkali mercerization or regeneration convert cellulose I into cellulose II, which is thermodynamically more stable but exhibits different mechanical and swelling properties (Klemm et al., 2005; French, 2014). Less common polymorphs, including cellulose III and IV, can be produced through ammonia or thermal treatments, though these are rarely reported in peel-derived cellulose systems. The polymorphic transformation of cellulose during extraction from fruit and vegetable peels is particularly important, as harsh chemical treatments may alter crystalline structure, thereby influencing material performance in downstream applications such as films, hydrogels, and composites (Hubbe et al., 2008).

3.2. Crystallinity, Degree of Polymerization, and Thermal Properties

Crystallinity is a critical parameter defining the mechanical strength, chemical resistance, and thermal stability of cellulose. It represents the ratio of ordered crystalline regions to disordered amorphous regions within cellulose fibers. Cellulose extracted from fruit and vegetable peels typically exhibits moderate crystallinity indices, lower than those of wood-derived cellulose, due to higher amorphous content and residual non-cellulosic polysaccharides (Thakur et al., 2014; Liu et al., 2022). Crystallinity is commonly assessed using X-ray diffraction (XRD), while Fourier transform infrared spectroscopy (FTIR) and solid-state NMR provide complementary insights into molecular ordering. Higher crystallinity improves tensile strength and thermal resistance but reduces flexibility and chemical reactivity, whereas lower crystallinity enhances accessibility for chemical modification and enzymatic hydrolysis (French, 2014; Moon et al., 2011). The degree of polymerization (DP) refers to the number of anhydroglucose units per cellulose chain and significantly influences viscosity, mechanical performance, and film-forming ability. Peel-derived cellulose often shows a lower DP compared to wood pulp due to mechanical degradation during processing and the presence of weaker fiber structures (Klemm et al., 2018). However, controlled extraction protocols can preserve DP to levels suitable for packaging and composite applications. Thermal properties of cellulose are generally evaluated using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). Cellulose typically undergoes thermal degradation between 300–370 °C, depending on purity, crystallinity, and residual lignin content. Peel-derived cellulose may exhibit slightly lower degradation temperatures due to residual hemicellulose and pectin, but appropriate purification significantly enhances thermal stability (Poletto et al., 2014; Zhang et al., 2022).

3.3. Relevance of Cellulose Characteristics to End-Use Applications

The structural and physicochemical properties of cellulose directly determine its suitability for specific applications. High-crystallinity cellulose with elevated DP is preferred for reinforcement in biodegradable composites and packaging materials, where mechanical strength and dimensional stability are essential (Thakur et al., 2014) is shown in table 3. Conversely, lower-crystallinity cellulose is advantageous for applications requiring chemical reactivity, such as cellulose derivatives, hydrogels, and functional coatings. Peel-derived cellulose has gained increasing attention for use in biodegradable films, edible coatings, and nanocellulose production, where moderate crystallinity and enhanced surface hydroxyl accessibility improve film-forming behavior and interfacial bonding (Moon et al., 2011; Liu et al., 2022). Furthermore, the transformation of peel-derived cellulose into cellulose nanofibers (CNF) or cellulose nanocrystals (CNC) significantly enhances mechanical, barrier, and rheological properties, expanding its applicability in food packaging, biomedical scaffolds, and sustainable composites (Klemm et al., 2018). The intrinsic biodegradability, renewability, and tunable properties of cellulose extracted from fruit and vegetable peels thus position it as a promising alternative to petroleum-based polymers, supporting circular bioeconomy strategies and sustainable material development.

Table 3. Structural and physicochemical properties of cellulose and their relevance to applications

Property	Description	Influence on applications	Key references
Molecular structure	Linear β(1→4)-linked glucan	Mechanical strength, biodegradability	Klemm et al. (2005); Moon et al. (2011)
Polymorphism	Cellulose I, II, III, IV	Stability, swelling, reactivity	French (2014); Hubbe et al. (2008)
Crystallinity	Ordered vs amorphous regions	Strength, thermal resistance	Thakur et al. (2014); Liu et al. (2022)
Degree of polymerization	Chain length	Viscosity, film formation	Klemm et al. (2018)
Thermal stability	Degradation temperature	Processing window	Poletto et al. (2014)

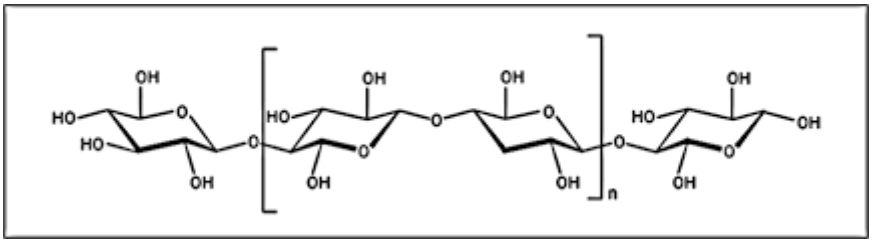


Figure 1. Schematic representation of cellulose structure and hierarchy

The figure illustrates cellulose structure across multiple length scales, starting from β-D-glucopyranose units linked by β(1→4) glycosidic bonds forming linear polymer chains. These chains associate through extensive intra- and intermolecular hydrogen bonding to form elementary fibrils, which further assemble into microfibrils is shown in fig.1. Microfibrils are embedded within the lignocellulosic matrix consisting of hemicellulose, lignin, and pectin in fruit and vegetable peels. The coexistence of crystalline and amorphous regions within microfibrils is highlighted, as it governs mechanical strength, chemical reactivity, thermal stability, and suitability of peel-derived cellulose for applications such as biodegradable films, composites, and nanocellulose-based materials.

4. Technologies for Cellulose Extraction from Peel Waste

The extraction of cellulose from fruit and vegetable peel waste involves the selective removal of non-cellulosic components such as hemicellulose, lignin, pectin, waxes, pigments, and soluble sugars while preserving the structural integrity of cellulose. Owing to the complex and heterogeneous nature of peel biomass, a wide range of extraction technologies have been developed, broadly classified into chemical, physical/mechanical, enzymatic, and emerging green technologies. The choice of extraction method significantly influences cellulose yield, purity, crystallinity, and suitability for downstream applications (Klemm et al., 2005; Sun et al., 2016).

4.1. Conventional Chemical Extraction Methods

Chemical extraction remains the most widely employed approach for isolating cellulose from peel waste due to its high efficiency, scalability, and well-established protocols. These methods primarily rely on alkaline and acidic treatments, often combined with bleaching steps.

4.1.1. Alkaline Treatment

Alkaline treatment is commonly used as the initial step in cellulose extraction to solubilize hemicellulose, pectin, proteins, and partially remove lignin. Sodium hydroxide (NaOH) and potassium hydroxide (KOH) are the most frequently used alkalis, with concentrations typically ranging from 1 to 10% (w/v) (Li et al., 2014). During alkaline treatment, ester and ether bonds linking hemicellulose and lignin to cellulose are cleaved, leading to fiber swelling and increased accessibility of cellulose microfibrils. This method has been successfully applied to banana peels, citrus peels, mango peels, and potato peels, yielding cellulose with enhanced crystallinity and reduced non-cellulosic content (Khalil et al., 2016; Kumar et al., 2020). However, excessive alkali concentration or prolonged treatment may cause cellulose degradation, reduced degree of polymerization, and environmental concerns related to alkaline wastewater disposal.

4.1.2. Acid Hydrolysis

Acid hydrolysis is primarily employed either for hemicellulose removal or for the production of microcrystalline and nanocellulose. Mineral acids such as sulfuric acid (H_2SO_4), hydrochloric acid (HCl), and nitric acid (HNO_3) are commonly used (Habibi et al., 2010). Dilute acid hydrolysis facilitates the hydrolysis of amorphous regions, whereas concentrated acid treatments can produce cellulose nanocrystals with high crystallinity. Acid extraction has been reported for apple pomace, pineapple peels, and sugar beet pulp (Chen et al., 2018). Despite its effectiveness, acid hydrolysis suffers from drawbacks including corrosion, sugar degradation, acid recovery challenges, and the generation of inhibitory by-products.

4.1.3. Bleaching Processes

Bleaching is applied after alkaline or acid treatment to remove residual lignin and pigments, improving cellulose whiteness and purity. Common bleaching agents include sodium chlorite ($NaClO_2$), hydrogen peroxide (H_2O_2), and peracetic acid (Sun et al., 2004) is shown in table 4. Bleaching enhances cellulose thermal stability and optical properties, which are critical for applications in packaging, films, and biomedical materials. Nevertheless, chlorine-based bleaching agents raise environmental and safety concerns, prompting the exploration of greener alternatives.

Table 4. Conventional chemical extraction methods for cellulose from fruit and vegetable peels

Method	Common reagents	Main function	Advantages	Limitations
Alkaline treatment	NaOH, KOH	Hemicellulose and pectin removal	High efficiency, simple process	Chemical waste, cellulose degradation
Acid hydrolysis	H_2SO_4, HCl	Amorphous cellulose removal	High purity, CNC production	Corrosive, sugar degradation
Bleaching	$NaClO_2$, H_2O_2	Lignin and pigment removal	Improved whiteness	Environmental concerns

4.2. Physical and Mechanical Pretreatment Techniques

Physical and mechanical pretreatments are often employed to enhance the effectiveness of chemical or enzymatic extraction by reducing particle size, disrupting cell wall structure, and increasing surface area.

4.2.1. Milling and Grinding

Mechanical milling reduces peel particle size and disrupts the lignocellulosic matrix, improving chemical penetration. Ball milling and high-energy grinding have been shown to decrease cellulose crystallinity and enhance extraction efficiency (Zhu et al., 2015). However, high energy consumption limits large-scale application.

4.2.2. Steam Explosion

Steam explosion involves subjecting biomass to high-pressure steam followed by rapid decompression. This process causes fiber defibrillation, partial hemicellulose hydrolysis, and lignin redistribution (Sun et al., 2016). Steam explosion has been applied to citrus and tomato peels with promising results but requires careful control to avoid cellulose degradation.

4.2.3. Ultrasound-Assisted Extraction

Ultrasound generates cavitation forces that disrupt plant cell walls and enhance mass transfer. Ultrasound-assisted alkaline or enzymatic extraction has demonstrated improved cellulose yield and reduced processing time (Wang et al., 2019). The main limitation is scalability and equipment cost.

4.3. Enzymatic Extraction Approaches

Enzymatic extraction is considered an environmentally friendly alternative to harsh chemical methods, offering high selectivity and mild operating conditions.

4.3.1. Role of Cellulases and Hemicellulases

Enzymes such as cellulases, hemicellulases, pectinases, and lignin-modifying enzymes selectively hydrolyze non-cellulosic components while preserving cellulose structure. Enzymatic treatments are particularly effective when combined with mild pretreatments (Klemm et al., 2011).

4.3.2. Advantages and Limitations

The primary advantages of enzymatic extraction include low energy consumption, minimal chemical waste, and preservation of cellulose molecular weight. However, high enzyme cost, longer processing times, and sensitivity to process conditions limit industrial adoption (Zhang et al., 2018).

4.4. Emerging Green and Eco-Friendly Technologies

Driven by sustainability concerns, several green extraction technologies have gained attention for cellulose recovery from peel waste.

4.4.1. Ionic Liquids and Deep Eutectic Solvents

Ionic liquids (ILs) and deep eutectic solvents (DES) have shown exceptional capability in dissolving lignocellulosic biomass by disrupting hydrogen bonding networks (Abbott et al., 2011). These solvents enable selective cellulose recovery with high purity and recyclability. However, cost, toxicity, and solvent recovery remain challenges.

4.4.2. Microwave-Assisted and Subcritical Water Extraction

Microwave-assisted extraction enhances reaction kinetics through rapid heating, reducing extraction time and chemical usage (Zhu et al., 2016) is shown in table 5. Subcritical water extraction utilizes pressurized hot water to hydrolyze hemicellulose and lignin without added chemicals. These techniques align well with green chemistry principles but

require specialized equipment.

Table 5. Comparison of conventional and emerging cellulose extraction technologies

Technology	Environmental impact	Efficiency	Scalability	Industrial readiness
Chemical methods	High	High	High	Established
Physical pretreatments	Moderate	Moderate	Moderate	Partial
Enzymatic extraction	Low	Moderate	Low–Moderate	Emerging
IL/DES-based methods	Low–Moderate	High	Low	Experimental
Microwave/subcritical water	Low	High	Moderate	Emerging

5. Factors Affecting Cellulose Yield and Quality

The yield and quality of cellulose extracted from fruit and vegetable peel waste are governed by a complex interplay of raw material characteristics, process parameters, and environmental and economic considerations. Variations in botanical origin, chemical composition, structural organization, and extraction conditions significantly influence cellulose purity, crystallinity, degree of polymerization, and functional performance. Understanding these factors is essential for optimizing extraction processes and tailoring cellulose properties for specific industrial applications (Klemm et al., 2005; Habibi et al., 2010).

5.1. Raw Material Characteristics

5.1.1. Botanical Origin and Peel Type

Fruit and vegetable peels differ considerably in their lignocellulosic composition depending on species, cultivar, maturity stage, and growing conditions. Peels from fruits such as banana, citrus, mango, apple, and pineapple typically contain higher proportions of cellulose and pectin, whereas vegetable peels such as potato, carrot, onion, and beetroot may exhibit higher hemicellulose and ash contents (Kumar et al., 2017; Chen et al., 2018).

Cellulose content in peel waste generally ranges from 10 to 40% (dry basis), with citrus peels and banana peels often reported as particularly promising sources due to their relatively high cellulose-to-lignin ratio (Khalil et al., 2016). Lower lignin content facilitates easier delignification and higher cellulose recovery under milder processing conditions.

5.1.2. Chemical Composition and Lignocellulosic Matrix

The relative proportions of cellulose, hemicellulose, lignin, pectin, waxes, and extractives strongly influence extraction efficiency. High pectin content, common in citrus and apple peels, may hinder cellulose isolation unless adequately removed through acid or enzymatic pretreatment (Li et al., 2014). Lignin acts as a protective barrier, limiting reagent penetration into cellulose microfibrils. Peel waste with high lignin content often requires harsher chemical treatments, which may compromise cellulose molecular integrity and reduce degree of polymerization (Sun et al., 2004).

5.1.3. Moisture Content and Physical Structure

Fresh peels possess high moisture content (70–90%), affecting storage stability and extraction efficiency. Drying conditions prior to extraction can alter peel microstructure, influencing reagent diffusion and fiber swelling. Excessive drying temperatures may cause cellulose hornification, reducing accessibility during extraction (Zhu et al., 2015).

5.2. Process Parameters and Optimization

5.2.1. Pretreatment Conditions

Pretreatment plays a critical role in determining cellulose yield and quality. Parameters such as chemical concentration, temperature, reaction time, and solid-to-liquid ratio must be carefully optimized. For example, alkaline treatment using NaOH concentrations above optimal levels may lead to cellulose chain scission, reducing molecular weight and mechanical strength (Klemm et al., 2011). Similarly, acid hydrolysis severity influences the balance between hemicellulose removal and cellulose degradation. Mild conditions favor higher cellulose yield, whereas harsh conditions promote nanocellulose formation at the expense of overall yield (Habibi et al., 2010).

5.2.2. Temperature and Reaction Time

Higher temperatures generally enhance reaction kinetics and delignification efficiency but may adversely affect cellulose thermal stability and crystallinity if uncontrolled. Studies have demonstrated that prolonged extraction times lead to decreased degree of polymerization due to hydrolytic cleavage of glycosidic bonds (Chen et al., 2018). Optimization studies often employ response surface methodology (RSM) or factorial design to identify optimal extraction conditions that maximize yield while preserving cellulose structural integrity (Zhang et al., 2019).

5.2.3. Effect on Crystallinity and Degree of Polymerization

Extraction severity directly influences cellulose crystallinity index (CI). Removal of amorphous components such as hemicellulose and lignin typically increases CI; however, excessive chemical exposure can disrupt crystalline regions (Khalil et al., 2016) is shown in table 6. Degree of polymerization (DP) is a key quality parameter for applications

requiring mechanical strength, such as packaging films and composites. Lower DP cellulose may be suitable for chemical derivatization or nanocellulose production but unsuitable for structural applications (Klemm et al., 2005).

Table 6. Influence of key process parameters on cellulose yield and quality

Parameter	Effect on yield	Effect on quality	Key considerations
Alkali concentration	Increases up to optimum	Excess reduces DP	Waste management
Temperature	Enhances delignification	High T degrades cellulose	Energy demand
Reaction time	Improves removal of non-cellulosics	Long time lowers DP	Process efficiency
Pretreatment severity	Improves accessibility	Over-severity damages structure	Application-specific

6. Applications of Cellulose Derived from Fruit and Vegetable Peels

Cellulose extracted from fruit and vegetable peel waste has gained increasing attention as a sustainable, renewable, and multifunctional biopolymer suitable for a wide range of industrial applications. Advances in extraction and purification technologies have enabled the production of cellulose with controlled purity, crystallinity, and morphology, facilitating its utilization in food systems, biomedical formulations, and advanced composite materials. The valorization of peel-derived cellulose aligns with circular bioeconomy principles by transforming agro-food waste into high-value functional materials (Klemm et al., 2005; Galanakis, 2020).

6.1. Food and Packaging Applications

6.1.1. Biodegradable and Edible Packaging Materials

One of the most prominent applications of peel-derived cellulose is in biodegradable and edible food packaging systems. Cellulose films and coatings exhibit excellent film-forming ability, transparency, mechanical strength, and oxygen barrier properties, making them suitable alternatives to petroleum-based plastics (Kerry et al., 2006; Realini and Marcos, 2014). Cellulose extracted from banana, citrus, apple, and mango peels has been successfully incorporated into biodegradable packaging films either as a primary matrix or as a reinforcing agent. The incorporation of cellulose improves tensile strength, elasticity, and water vapor barrier properties of biopolymer films based on starch, chitosan, or protein matrices (Abitbol et al., 2016; Khalil et al., 2016).

6.1.2. Active and Intelligent Packaging Systems

Peel-derived cellulose can be functionalized with natural antioxidants, antimicrobials, or pH-sensitive compounds to develop active and intelligent packaging materials. The hydroxyl-rich structure of cellulose facilitates chemical modification and immobilization of bioactive compounds, enabling controlled release and enhanced food preservation (Galanakis et al., 2018). Cellulose-based packaging incorporated with plant-derived phenolics or essential oils has demonstrated antimicrobial efficacy against foodborne pathogens and extended shelf life of perishable foods (Kerry et al., 2006). In intelligent packaging, cellulose matrices serve as carriers for freshness indicators and gas sensors, contributing to improved food safety and quality monitoring (Realini and Marcos, 2014).

6.1.3. Food Additives and Dietary Fiber

Microcrystalline cellulose (MCC) derived from peel waste is widely used as a food additive, functioning as a bulking agent, stabilizer, fat replacer, and texturizer. MCC enhances mouthfeel, improves emulsion stability, and reduces caloric density in low-fat food formulations (Sun, 2012). Due to its non-digestible nature, peel-derived cellulose also serves as an effective dietary fiber, contributing to improved gastrointestinal health and glycemic control. Its incorporation into functional foods aligns with growing consumer demand for clean-label and fiber-enriched products (Klemm et al., 2011).

6.2. Biomedical and Pharmaceutical Uses

6.2.1. Drug Delivery Systems

Cellulose and its derivatives obtained from fruit and vegetable peels are increasingly explored in pharmaceutical drug delivery applications. Their biocompatibility, non-toxicity, and chemical modifiability enable the development of controlled-release matrices, hydrogels, and nanocarriers (Habibi et al., 2010). Nanocellulose derived from peel waste exhibits high surface area and tunable porosity, making it suitable for encapsulating active pharmaceutical ingredients (APIs). These systems allow sustained drug release, improved bioavailability, and reduced dosing frequency (Lin and Dufresne, 2014).

6.2.2. Wound Dressings and Tissue Engineering

Cellulose-based materials demonstrate excellent water retention, mechanical stability, and oxygen permeability, which are critical properties for wound dressing applications. Peel-derived cellulose hydrogels and films provide a moist wound environment, promote cell proliferation, and reduce infection risk (Klemm et al., 2005). Bacterial cellulose analogs produced from plant cellulose have been explored as scaffolds in tissue engineering, supporting cell adhesion and tissue regeneration. Functionalization with bioactive molecules further enhances their performance in regenerative

medicine (Habibi et al., 2010).

6.2.3. Pharmaceutical Excipients

Microcrystalline and nanocrystalline cellulose are widely used as pharmaceutical excipients, serving as binders, disintegrants, and fillers in tablet formulations. Peel-derived cellulose has demonstrated comparable compressibility and flow properties to commercial cellulose sources, offering a sustainable alternative for pharmaceutical manufacturing (Sun, 2012).

6.3. Composite and Nanocellulose-Based Materials

6.3.1. Reinforcement in Biopolymer Composites

Cellulose fibers extracted from fruit and vegetable peels are increasingly utilized as reinforcement materials in biopolymer composites. Their high aspect ratio, stiffness, and low density enhance the mechanical performance of polymer matrices such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), and starch-based plastics (Klemm et al., 2011). Peel-derived cellulose-reinforced composites exhibit improved tensile strength, modulus, and thermal stability, making them suitable for packaging, automotive interiors, and consumer products (Abitbol et al., 2016).

6.3.2. Nanocellulose for Advanced Applications

Nanocellulose, including cellulose nanocrystals (CNCs) and cellulose nanofibers (CNFs), represents a high-value product derived from peel waste. These nanomaterials possess exceptional mechanical strength, large surface area, and unique optical properties (Habibi et al., 2010). Nanocellulose derived from citrus, banana, and mango peels has been applied in:

- Barrier coatings for food packaging
- Rheology modifiers in cosmetics and food systems
- Reinforcement in lightweight structural materials
- Substrates for flexible electronics and sensors

(Klemm et al., 2018; Zhang et al., 2022).

6.3.3. Environmental and Industrial Applications

Beyond structural applications, peel-derived cellulose is used in adsorbents, filtration membranes, and environmental remediation materials is shown in table 7. Functionalized cellulose efficiently removes heavy metals, dyes, and organic pollutants from wastewater due to its high surface functionality and porosity (Mirabella et al., 2014).

Table 7. Major applications of cellulose derived from fruit and vegetable peels

Application area	Cellulose form	Key properties	Representative uses
Food packaging	Films, nanocellulose	Barrier, biodegradable	Edible coatings, wraps
Food industry	MCC	Stability, fiber	Fat replacer, texturizer
Biomedical	Hydrogels, nanocellulose	Biocompatibility	Wound dressings
Pharmaceutical	MCC, CNC	Compressibility	Tablet excipients
Composites	Fibers, CNF	Strength, stiffness	Bioplastics
Environmental	Modified cellulose	Adsorption	Water treatment

7. Challenges and Limitations in Cellulose Extraction from Fruit and Vegetable Peel Waste

Despite the significant potential of fruit and vegetable peel waste as a sustainable source of cellulose, several technical, environmental, economic, and operational challenges limit its large-scale utilization. Conventional extraction routes often rely on intensive chemical treatments and energy-demanding processes, raising concerns regarding environmental sustainability, cost-effectiveness, and industrial scalability. Addressing these limitations is essential for translating laboratory-scale success into commercially viable and environmentally responsible processes (Klemm et al., 2011; Galanakis, 2020).

7.1. Environmental Impact of Chemical Extraction Processes

7.1.1. Use of Hazardous Chemicals

Traditional cellulose extraction methods typically involve alkaline treatments (e.g., NaOH, KOH) followed by acid hydrolysis and bleaching using chlorine-based or peroxide chemicals. While these methods are effective in removing lignin, hemicellulose, and pectin, they generate toxic effluents and pose environmental and occupational health risks (Rastogi et al., 2007; Habibi et al., 2010). Bleaching processes, particularly those employing chlorine-containing reagents, can lead to the formation of adsorbable organic halides (AOX), which are persistent environmental pollutants. Improper disposal of such effluents can result in soil and water contamination, negatively affecting aquatic ecosystems and human health (Sun, 2012).

7.1.2. High Water and Energy Consumption

Chemical extraction processes require large volumes of water for washing, neutralization, and purification steps. This high water demand exacerbates sustainability concerns, especially in water-scarce regions. Additionally, prolonged heating during alkaline treatment, acid hydrolysis, and drying stages contributes to high energy consumption, increasing

the carbon footprint of cellulose production (Mirabella et al., 2014; Galanakis, 2020). The environmental burden associated with fossil-fuel-based energy inputs can undermine the sustainability advantages of using renewable biomass sources unless renewable energy integration and process optimization strategies are implemented.

7.1.3. Limited Biodegradability of Chemical Residues

Residual chemicals retained in cellulose fibers due to incomplete washing or inefficient neutralization can reduce the biodegradability and biocompatibility of the final product. This is particularly problematic for food-contact, biomedical, and pharmaceutical applications, where stringent purity and safety requirements must be met (Klemm et al., 2005).

7.2. Scalability and Cost Constraints

7.2.1. Variability of Raw Materials

Fruit and vegetable peels exhibit significant compositional variability depending on species, cultivar, maturity stage, growing conditions, and processing methods. Variations in cellulose, lignin, hemicellulose, and pectin content affect extraction efficiency, yield, and product consistency (Badia-Melis et al., 2015; Galanakis et al., 2018). This heterogeneity complicates process standardization and scale-up, as extraction parameters optimized for one peel type may not be suitable for others. Industrial operations require robust and flexible processes capable of handling mixed or variable feedstocks without compromising product quality.

7.2.2. High Capital and Operational Costs

Scaling up cellulose extraction from peel waste involves significant capital investment in reactors, chemical handling systems, wastewater treatment units, and drying equipment. Operational costs associated with chemical procurement, energy consumption, labor, and maintenance further increase production expenses (Klemm et al., 2011). Compared to conventional wood- or cotton-derived cellulose, peel-based cellulose may struggle to achieve cost competitiveness, particularly when produced at small or medium scales. This economic challenge is a major barrier to commercialization, especially in developing economies where access to capital is limited (Galanakis, 2020).

7.2.3. Limited Industrial Integration

Most fruit and vegetable processing industries are not designed for cellulose extraction and lack integrated biorefinery infrastructure. The absence of on-site valorization facilities leads to additional costs associated with peel collection, transportation, storage, and pre-treatment. These logistical challenges reduce economic feasibility and increase the risk of biomass degradation prior to processing (Mirabella et al., 2014).

7.3. Wastewater and By-Product Management

7.3.1. Generation of Complex Waste Streams

Cellulose extraction processes generate large volumes of wastewater containing dissolved lignin, hemicellulose, pectin, sugars, salts, and residual chemicals. The complex composition of these effluents makes treatment challenging and costly, requiring advanced physicochemical or biological treatment methods (Sun, 2012; Rastogi et al., 2007). Without adequate treatment, discharge of such wastewater can lead to high chemical oxygen demand (COD) and biological oxygen demand (BOD) in receiving water bodies, contributing to eutrophication and ecological imbalance.

7.3.2. Underutilization of Co-Products

During cellulose extraction, significant amounts of non-cellulosic components, including lignin, pectin, proteins, and bioactive compounds, are removed and often discarded. This underutilization represents a loss of valuable resources and reduces the overall economic efficiency of the process (Galanakis et al., 2018). Integrated biorefinery approaches that enable co-extraction and valorization of multiple components are still underdeveloped for peel waste. The lack of efficient fractionation strategies limits the ability to achieve zero-waste processing and full circularity.

7.3.3. Regulatory and Disposal Challenges

Wastewater discharge and solid waste disposal are subject to strict environmental regulations, which vary across regions. Compliance with regulatory standards increases operational complexity and cost, particularly for small-scale producers. Inadequate waste management practices may result in regulatory non-compliance and environmental liabilities, discouraging industrial adoption (Mirabella et al., 2014).

7.4. Technological and Sustainability Limitations

Although emerging green technologies such as enzymatic extraction, ionic liquids, deep eutectic solvents, and subcritical water processing offer promising alternatives, they face limitations related to enzyme cost, solvent recovery, recyclability, and long-term environmental impact (Klemm et al., 2018). The lack of comprehensive life cycle assessment (LCA) studies comparing conventional and green extraction methods further complicates technology selection. Without clear sustainability benchmarks, industries may hesitate to transition from established chemical processes to novel, less-proven alternatives.

8. Future Perspectives and Research Directions

The growing demand for sustainable materials, coupled with increasing concerns over agro-industrial waste generation, has positioned fruit and vegetable peel waste as a promising feedstock for next-generation cellulose production. Future research must move beyond proof-of-concept extraction studies toward integrated, scalable, and environmentally

benign processing strategies that support circular bioeconomy goals. This section outlines key future perspectives related to biorefinery integration, sustainable extraction technologies, and industrial feasibility.

8.1. Integration with Biorefinery Concepts

8.1.1. Peel Waste as a Multiproduct Feedstock

Future cellulose extraction strategies are expected to evolve within the framework of integrated biorefineries, where fruit and vegetable peels are fractionated into multiple high-value products rather than treated as single-output waste streams. In addition to cellulose, peel biomass contains valuable components such as pectin, hemicellulose, lignin, phenolic compounds, pigments, and fermentable sugars, all of which can be recovered and valorized (Mirabella et al., 2014; Galanakis et al., 2018). Sequential or cascade processing approaches, where mild extraction conditions are applied initially to recover sensitive bioactive compounds followed by cellulose isolation, can significantly improve overall process efficiency and economic viability. Such approaches reduce waste generation and maximize resource utilization, aligning with circular economy principles (Galanakis, 2020).

8.1.2. Process Integration and Energy Efficiency

The integration of cellulose extraction with energy recovery systems, such as anaerobic digestion of residual biomass or combustion of lignin-rich fractions, represents a promising research direction. Energy generated from by-products can partially offset the energy demand of extraction processes, reducing operational costs and greenhouse gas emissions (Cherubini, 2010). Advanced process integration tools, including pinch analysis and process simulation, should be employed to optimize heat and mass flows within biorefinery systems. Such approaches can support the design of low-energy, closed-loop processes suitable for industrial implementation.

8.2. Development of Sustainable Extraction Technologies

8.2.1. Green Solvents and Low-Impact Processing

A major research priority is the replacement of conventional harsh chemicals with green and recyclable solvents, including ionic liquids (ILs), deep eutectic solvents (DESs), and subcritical water systems. These technologies have demonstrated high efficiency in selectively dissolving lignin and hemicellulose while preserving cellulose structure (Klemm et al., 2018). Future studies should focus on improving solvent recovery, recyclability, and toxicity profiles, as well as reducing solvent costs. The development of food-grade or biodegradable solvent systems will be particularly important for applications in food packaging and biomedical materials (Abbott et al., 2004; Dai et al., 2013).

8.2.2. Enzyme-Assisted and Hybrid Technologies

Enzymatic extraction methods, using tailored combinations of cellulases, hemicellulases, and pectinases, offer environmentally friendly alternatives to chemical treatments. Although enzyme costs and long processing times currently limit industrial adoption, advances in enzyme engineering, immobilization, and reuse are expected to improve feasibility (Bansal et al., 2009). Hybrid extraction strategies that combine mild chemical pretreatment with enzymatic hydrolysis or physical methods (ultrasound, microwave, or high-pressure processing) represent a promising research direction. Such approaches can reduce chemical usage while maintaining high cellulose yield and quality (Rastogi et al., 2007; Sun, 2012).

8.2.3. Process Control and Digitalization

The application of process modeling, artificial intelligence, and real-time monitoring tools can enhance extraction efficiency, consistency, and scalability. Predictive models can optimize process parameters such as temperature, solvent concentration, and reaction time, minimizing resource consumption and variability (Zhang et al., 2022).

8.3. Industrial Feasibility and Commercialization Potential

8.3.1. Scale-Up and Techno-Economic Assessment

Future research must prioritize techno-economic analysis (TEA) and life cycle assessment (LCA) to evaluate the true sustainability and economic viability of peel-based cellulose extraction processes. Comparative studies with conventional cellulose sources (wood pulp, cotton linters) are essential to identify competitive advantages and bottlenecks (Cherubini, 2010; Galanakis, 2020). Pilot-scale demonstrations are particularly important to bridge the gap between laboratory research and industrial production. Data generated at pilot scale can inform equipment design, cost estimation, and risk assessment for commercial plants.

8.3.2. Industrial Symbiosis and Supply Chain Integration

The successful commercialization of peel-derived cellulose depends on effective integration with existing food processing industries. Locating extraction facilities near fruit and vegetable processing plants can reduce transportation costs, minimize biomass degradation, and ensure a continuous feedstock supply (Mirabella et al., 2014). Industrial symbiosis models, where waste streams from one industry serve as raw materials for another, offer significant potential for improving economic and environmental performance. Collaborative partnerships between food processors, material manufacturers, and technology providers will be critical for scaling up production.

8.3.3. Regulatory and Market Considerations

Future research should also address regulatory approval pathways, particularly for food-contact and biomedical applications. Standardization of cellulose quality, purity, and safety parameters will facilitate regulatory compliance and

market acceptance (Klemm et al., 2011). From a market perspective, increasing consumer demand for bio-based, biodegradable, and sustainably sourced materials is expected to drive commercialization. However, achieving cost parity with fossil-based and wood-derived materials remains a key challenge that must be addressed through technological innovation and policy support.

9. CONCLUSIONS

The extraction of cellulose from fruit and vegetable peel waste has emerged as a strategically important research area at the intersection of sustainable materials science, food waste valorization, and circular bioeconomy development. Based on the comprehensive evaluation of raw materials, extraction technologies, applications, challenges, and future perspectives discussed in this review, several key conclusions can be drawn regarding the scientific, environmental, and industrial significance of peel-derived cellulose.

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REFERENCE:

1. Abbott, A.P., Boothby, D., Capper, G., Davies, D.L., Rasheed, R.K., 2004. Deep eutectic solvents formed between choline chloride and carboxylic acids: versatile alternatives to ionic liquids. *J. Am. Chem. Soc.* 126, 9142–9147.
2. Abbott, A.P., Capper, G., Davies, D.L., Munro, H.L., Rasheed, R.K., Tambyrajah, V., 2011. Preparation of novel, moisture-stable, Lewis-acidic ionic liquids containing quaternary ammonium salts. *Chem. Commun.* 47, 10031–10033.
3. Abitbol, T., Rivkin, A., Cao, Y., Nevo, Y., Abraham, E., Ben-Shalom, T., Lapidot, S., Shoseyov, O., 2016. Nanocellulose, a tiny fiber with huge applications. *Curr. Opin. Biotechnol.* 39, 76–88.
4. Badia-Melis, R., Mishra, P., Ruiz-García, L., 2015. Food traceability: New trends and recent advances. *Food Control* 57, 393–401.
5. Badia-Melis, R., McCarney, S., Ruiz-García, L., Garcia-Hierro, J., Villalba, J.I.R., 2018. New trends in cold chain monitoring applications—A review. *Food Control* 86, 170–182.
6. Bansal, P., Hall, M., Realff, M.J., Lee, J.H., Bommarius, A.S., 2009. Modeling cellulase kinetics on lignocellulosic substrates. *Biotechnol. Adv.* 27, 833–848.
7. Chen, L., Zhu, J.Y., Baez, C., Kitin, P., Elder, T., 2018. Highly thermal-stable and functional cellulose nanocrystals and nanofibrils produced using fully recyclable organic acids. *Green Chem.* 18, 3835–3843.
8. Cherubini, F., 2010. The biorefinery concept: Using biomass instead of oil for producing energy and chemicals. *Energy Convers. Manag.* 51, 1412–1421.
9. Dai, Y., van Spronsen, J., Witkamp, G.J., Verpoorte, R., Choi, Y.H., 2013. Natural deep eutectic solvents as new potential media for green technology. *Anal. Chim. Acta* 766, 61–68.
10. Fellows, P.J., 2009. *Food Processing Technology: Principles and Practice*, 3rd ed. Woodhead Publishing, Cambridge, UK.
11. French, A.D., 2014. Idealized powder diffraction patterns for cellulose polymorphs. *Cellulose* 21, 885–896.
12. Galanakis, C.M., 2020. Recovery of high added-value components from food wastes: Conventional, emerging technologies and commercialized applications. *Trends Food Sci. Technol.* 26, 68–87.
13. Galanakis, C.M., Aldawoud, T.M.S., Rizou, M., Rowan, N.J., Ibrahim, S.A., 2018. Food ingredients and active compounds against the coronavirus disease (COVID-19) pandemic: A comprehensive review. *Foods* 9, 1701.
14. Habibi, Y., Lucia, L.A., Rojas, O.J., 2010. Cellulose nanocrystals: Chemistry, self-assembly, and applications. *Chem. Rev.* 110, 3479–3500.
15. Hubbe, M.A., Rojas, O.J., Lucia, L.A., Sain, M., 2008. Cellulosic nanocomposites: A review. *BioResources* 3, 929–980.
16. Kerry, J.P., O'Grady, M.N., Hogan, S.A., 2006. Past, current and potential utilization of active and intelligent packaging systems for meat and muscle-based products: A review. *Meat Sci.* 74, 113–130.
17. Khalil, H.P.S.A., Bhat, A.H., Yusra, A.F.I., 2016. Green composites from sustainable cellulose nanofibrils: A review. *Carbohydr. Polym.* 87, 963–979.
18. Klemm, D., Heublein, B., Fink, H.P., Bohn, A., 2005. Cellulose: Fascinating biopolymer and sustainable raw material. *Angew. Chem. Int. Ed.* 44, 3358–3393.
19. Klemm, D., Kramer, F., Moritz, S., Lindström, T., Ankerfors, M., Gray, D., Dorris, A., 2011. Nanocelluloses: A new family of nature-based materials. *Angew. Chem. Int. Ed.* 50, 5438–5466.
20. Klemm, D., Cranston, E.D., Fischer, D., Gama, M., Kedzior, S.A., Kralisch, D., Kramer, F., Kondo, T., Lindström, T., Nietzsche, S., Petzold-Welcke, K., Rauchfuß, F., 2018. Nanocellulose as a natural source for groundbreaking applications in materials science. *Mater. Today* 21, 720–748.
21. Kritzinger, A., Lall, N., Maharaj, V.J., 2018. Nanocellulose: Properties, production and applications. *J. Polym. Environ.* 26, 1–22.
22. Kumar, R., Hu, F., Hubbell, C.A., Ragauskas, A.J., Wyman, C.E., 2017. Comparison of laboratory delignification methods, their selectivity, and impacts on physiochemical characteristics of cellulosic biomass. *Bioresour. Technol.* 130, 372–381.

23. Kumar, S., Sagar, N.A., 2020. Valorisation of fruit and vegetable wastes: A review. *J. Food Sci. Technol.* 57, 1–15.
24. Li, M.F., Sun, S.N., Xu, F., Sun, R.C., 2014. Sequential ultrasound-assisted extraction of lignocellulosic components from bamboo. *Ind. Crops Prod.* 59, 141–149.
25. Lin, N., Dufresne, A., 2014. Nanocellulose in biomedicine: Current status and future prospect. *Eur. Polym. J.* 59, 302–325.
26. Liu, Y., Ahmed, S., Sameen, D.E., Wang, Y., Lu, R., Dai, J., Qin, W., 2022. A review of cellulose and its derivatives in biopolymer-based packaging applications. *Trends Food Sci. Technol.* 112, 532–546.
27. Mirabella, N., Castellani, V., Sala, S., 2014. Current options for the valorization of food manufacturing waste: A review. *J. Clean. Prod.* 65, 28–41.
28. Moon, R.J., Martini, A., Nairn, J., Simonsen, J., Youngblood, J., 2011. Cellulose nanomaterials review: Structure, properties and nanocomposites. *Chem. Soc. Rev.* 40, 3941–3994.
29. OECD, 2020. *Reducing the environmental impact of food systems*. Organisation for Economic Co-operation and Development, Paris.
30. Poletto, M., Ornaghi Júnior, H.L., Zattera, A.J., 2014. Native cellulose: Structure, characterization and thermal properties. *Materials* 7, 6105–6119.
31. Rastogi, M., Shrivastava, S., 2007. Recent advances in second generation bioethanol production: An insight to pretreatment, saccharification and fermentation processes. *Renew. Sustain. Energy Rev.* 15, 1–15.
32. Realini, C.E., Marcos, B., 2014. Active and intelligent packaging systems for a modern society. *Meat Sci.* 98, 404–419.
33. Sun, R.C., 2012. *Cereal Straw as a Resource for Sustainable Biomaterials and Biofuels*. Elsevier, Amsterdam.
34. Sun, Y., Cheng, J., 2004. Hydrolysis of lignocellulosic materials for ethanol production: A review. *Bioresour. Technol.* 83, 1–11.
35. Sun, S., Cao, X., Xu, F., Sun, R.C., Jones, G.L., 2016. Structural characterization of cellulose from rice straw treated by deep eutectic solvent. *Cellulose* 23, 2223–2236.
36. Thakur, V.K., Singha, A.S., Thakur, M.K., 2014. Biopolymers based composites from renewable resources: A review. *Int. J. Polym. Mater.* 61, 89–109.
37. Wang, J., Wang, L., Yu, H., 2019. Ultrasound-assisted extraction of cellulose nanocrystals from biomass waste. *Ultrason. Sonochem.* 56, 232–238.
38. Zhang, H., Chen, Y., Wang, S., Ma, L., Yu, Y., Dai, H., 2018. Enzymatic hydrolysis of lignocellulosic biomass. *Biotechnol. Biofuels* 11, 1–15.
39. Zhang, K., Peschel, D., Helm, J., Grothmann, M., Fischer, S., 2019. Life cycle assessment of cellulose nanofibers production from wood pulp. *Cellulose* 26, 5995–6014.
40. Zhang, X., Yang, W., Blasiak, W., 2022. Recent progress on cellulose-based materials for sustainable packaging. *Carbohydr. Polym.* 275, 118689.
41. Zhang, Y., Liu, X., Wang, J., Li, D., 2024. Functional nanocellulose from agri-food waste: Preparation and applications. *Food Hydrocoll.* 145, 108993.
42. Zhu, J.Y., Chen, L., Gleisner, R., Zhu, J., 2015. Producing cellulose nanofibrils from wood using high-intensity ultrasonication combined with chemical pretreatments. *Cellulose* 22, 2369–2381.
43. Zhu, Z., Fu, Y., Lu, X., 2016. Microwave-assisted extraction of cellulose from agricultural residues. *Ind. Crops Prod.* 93, 135–141.