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Advances in Cellulose Extraction from Banana Pseudo stem

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Abstract

The growing demand for sustainable, biodegradable alternatives to synthetic polymers has intensified interest in agro-waste materials as renewable sources of biopolymers. The banana pseudo stem, a typically discarded byproduct of banana cultivation, is a rich source of cellulose a key structural polysaccharide with wide-ranging industrial applications. This review highlights the significance of banana pseudo stem-derived cellulose, discussing its chemical composition, sustainability potential, and value addition. It provides a comparative overview of conventional and advanced extraction techniques, including chemical, enzymatic, mechanical, and green technologies such as ultrasound- and microwave-assisted methods. Key challenges in extraction, such as lignin removal, process optimization, and yield enhancement, are addressed. Finally, the review explores potential applications of extracted cellulose in fields such as biodegradable packaging, bio composites, biofilms, and pharmaceuticals, emphasizing its role in promoting circular economy practices and reducing environmental pollution.

Keywords: Biopolymers, Cellulose extraction, Biodegradability, Bio-composites, Food packaging, Environmental sustainability, Renewable resources, Waste valorizations

1. Introduction

The banana plant (*Musa* spp.), a large herbaceous species of the Musaceae family, is widely cultivated across more than 130 countries, particularly in tropical and subtropical regions (FAO, 2023) [27]. With global banana production reaching approximately 116.78 million tonnes annually, significant amounts of agro-industrial waste are generated, including pseudo stems (PS), peels, leaves, and husks, much of which is discarded through landfilling, burning, or dumping. These practices lead to environmental concerns such as soil contamination and greenhouse gas emissions (Kumar *et al*., 2020) [28].

Among these residues, the pseudo stem is the most abundant, comprising 60–80% of the plant's biomass (Nascimento *et al*., 2023) [24]. Rich in cellulose, it presents an opportunity for value-added applications such as fibre extraction for textiles, nanocomposite production, and biodegradable packaging (Ruangnarong *et al*., 2024) [26]. Since each banana plant produces only one fruit bunch in its lifetime, the pseudo stem is typically discarded post-harvest, contributing to environmental issues such as soil degradation, methane emissions, and inefficient resource utilization (Kumar *et al*., 2020) [28].

The banana pseudo stem is a lignocellulosic-rich material composed mainly of cellulose, hemicellulose, and lignin, making it a promising raw material for value-added applications (Sharma *et al*., 2021; Sogi, 2020) [29, 25]. Recent studies have explored its potential for fibre extraction, biofilm production, and nanocellulose synthesis, aligning with sustainable waste management strategies (Nascimento *et al*., 2023; Ruangnarong *et al*., 2024) [24, 26]. Despite its high cellulose content (32.4–64.0 wt %), variations in extraction methods significantly impact yield and purity (Singh *et al*., 2022) [30]. However, limited research has been conducted on the effect of particle size on cellulose recovery.

This review paper aims to provide a comprehensive analysis of banana pseudo stem valorisation, focusing on its composition, extraction techniques, and potential applications. By highlighting advancements in cellulose extraction and sustainable utilization strategies, this study contributes to circular economy principles and the global push for environmentally friendly material alternatives**.**

2. Importance of cellulose extraction for sustainable applications

Cellulose, the most abundant biopolymer on Earth, plays a crucial role in the transition towards sustainable materials and bio-based industries. Extracted primarily from plant biomass, cellulose serves as a renewable and biodegradable alternative to petroleum-based materials, making it highly valuable for sustainable applications (Klemm *et al*., 2005) [32]. The increasing environmental concerns regarding plastic pollution and resource depletion have intensified research efforts in utilizing cellulose for bioplastics, biomedical applications, and functional coatings (Jiang *et al*., 2020) [31].

A significant focus of recent studies has been on extracting cellulose from agricultural residues and industrial byproducts, such as banana pseudo stems, cauliflower stems, and sugarcane bagasse. These lignocellulosic waste materials present an eco-friendly alternative to wood-based cellulose, reducing deforestation and enhancing waste valorisation (Trache *et al*., 2016) [35]. Additionally, advancements in cellulose extraction techniques, including alkaline treatment, enzymatic hydrolysis, and ultrasound assisted extraction, have improved the yield and purity of cellulose, thereby expanding its applicability in various sustainable sectors (Sirviö *et al*., 2019) [34].

With the increasing global emphasis on circular economy principles, cellulose-based materials have gained attention for their applications in biodegradable packaging, water purification membranes, and bio-composites. Innovations in cellulose extraction and modification methods continue to drive progress in sustainable materials science (Sharma *et al*., 2021) [29].

This review focuses on recent advancements in cellulose extraction from banana pseudo stems, a significant agricultural waste product, with the goal of addressing key challenges such as low yield, high energy consumption, and environmental impacts of conventional chemical treatments (Polymers, 2024; Materials Proceedings, 2022) [52, 29]. In addition to extraction techniques, it examines the wide range of potential applications for banana-derived cellulose-including biodegradable food packaging and advanced bio-composites for industrial use (Heliyon, 2023) [39].

By evaluating how banana pseudo stems can be effectively utilized, this review highlights their potential for reducing agricultural waste and contributing to environmental sustainability. In doing so, it aligns with global circular economy strategies by emphasizing waste valorisation, resource optimization, and the development of renewable materials (Sustainable Materials and Technologies, 2023). Ultimately, the review seeks to bridge current knowledge gaps through a comparative analysis of extraction methodologies and their implications, guiding future research and innovation in cellulose-based materials. To better understand the valorisation potential of banana pseudo-stems, it is essential to examine their biochemical composition particularly their cellulose content.

3. Composition of Banana Pseudo stem

Banana pseudo-stems are rich in cellulose, a key structural component in plant cell walls. Studies have shown that the cellulose content in banana pseudo-stems varies significantly, ranging from approximately 31% to 64%, depending on factors such as the specific banana cultivar, the part of the pseudo-stem analysed, and the methods used for extraction and measurement (Li *et al*., 2010; Cordeiro *et al*., 2004) [40, 41]. For instance, research indicates that the outer bark of the pseudo-stem, which is richer in cellulose fibers, contains about 60–70% polysaccharides, justifying its potential for pulping applications (Cordeiro *et al*., 2004) [41]. The variability in cellulose content underscores the importance of standardized assessment methods when evaluating banana pseudo-stems for industrial applications such as pulp and paper production or as a source of natural Fibers (Badanayak *et al*., 2023) [45].

4. Factors affecting cellulose yield and quality

The extraction of cellulose from banana pseudo stem is influenced by several factors, including pretreatment methods, extraction techniques, and the inherent chemical composition of the biomass. Pretreatment processes such as acid, alkaline, and peroxide treatments play a crucial role in modifying the lignocellulosic structure, thereby affecting cellulose accessibility and purity. Alkaline pretreatment, particularly with sodium hydroxide (NaOH), has been shown to effectively remove lignin and hemicellulose, resulting in increased cellulose content and enhanced enzymatic digestibility (Skiba *et al*., 2022) [48]. For instance, studies have reported cellulose yields exceeding 75% using NaOH treatments (Skiba *et al*., 2022) [48]. Conversely, acid pretreatment, while efficient in hemicellulose removal, may lead to increased lignin content, potentially hindering cellulose extraction efficiency (Krässig & Kitchen, 1961). Hydrogen peroxide (H_2O_2) treatments, while yielding higher overall material mass, often result in lower cellulose purity due to the presence of residual non-cellulosic substances (Krystynowicz *et al*., 2002) [46]. The choice of extraction method also significantly impacts the yield and quality of cellulose. the high and variable cellulose content of banana pseudo-stems, particularly in the outer layers, optimizing extraction processes becomes essential to maximize cellulose yield and purity for industrial use.

5. Methods of Cellulose Extraction

5.1 Chemical methods alkaline treatment

The alkaline method of cellulose extraction is a widely used technique that involves treating lignocellulosic biomass, such as banana pseudo stem, rice straw, sugar palm fiber, or bagasse, with an alkaline solution, typically sodium hydroxide (NaOH), to remove lignin, hemicellulose, and other non-cellulosic components (Khan *et al*., 2022; Cabrera-Villamizar *et al*., 2024) [49, 52]. The process begins with preparing the biomass by washing, drying, and grinding it to increase surface area. The material is then treated with NaOH at elevated temperatures, usually around 80–100 °C, for several hours, which disrupts the lignocellulosic structure and selectively breaks down lignin and hemicellulose (Melikoğlu *et al*., 2019; Melesse *et al*., 2022) [50, 51].

After the alkaline treatment, bleaching with agents like hydrogen peroxide (H_2O_2) may be used to further purify the cellulose by removing any remaining lignin and improving its whiteness and purity (Khan *et al*., 2022) [49]. The final cellulose product is washed to neutralize excess alkali, filtered, and dried. This method is effective for producing high-purity cellulose, which can be used in various applications, such as biocomposites, nanocellulose production, and biodegradable materials (Melikoğlu *et al*., 2019) [50].

The alkaline extraction method is widely valued for its simplicity, cost-effectiveness, and sustainability, making it a popular choice for biomass fractionation and cellulose isolation (Khan *et al*., 2022) [49]. It enables the production of high-purity cellulose from various agricultural residues by effectively removing lignin and hemicellulose with minimal cellulose degradation an essential factor for applications in biodegradable materials and composites (Melesse *et al*., 2022) [51]. The process is straightforward, using sodium hydroxide as the primary reagent, which is both affordable and readily available. By adjusting parameters such as NaOH concentration, temperature, and enzymatic treatment, the method can be optimized to maximize yield and purity. Moreover, it supports the valorisation of agricultural waste, contributing to the circular bioeconomy by converting low-value biomass into valuable resources (Cabrera-Villamizar *et al*., 2024) [52].

Despite its benefits, the method requires careful optimization of parameters such as temperature, alkali concentration, and treatment duration to avoid cellulose degradation (Melikoğlu *et al*., 2019) [50]. Post-treatment steps like bleaching and washing further enhance the purity of the cellulose, making it suitable for advanced applications like nanocellulose production, bio-based packaging, and as a reinforcing agent in polymer matrix composites (Khan *et al*., 2022; Cabrera-Villamizar *et al*., 2024) [49, 52].

Table 1: Effect of NaOH Concentration, Temperature, and Time on Cellulose Yield from Banana Pseudo stem

Sl. no	NaOH (%)	Temp (°C)	Time (min)	Cellulose Yield (%)	Conclusion
1.	6	90	240	32.64	Highest yield achieved under mild NaOH (6%)
2.	12	60	135	30.84	High yield and good cellulose under higher NaOH with moderate temp/time; slightly lower whiteness index possibly due partial hemicellulose retention
3.	9	90	30	33.17	Short time and high temp combination yielded good results; high whiteness suggests effective bleaching and partial degradation of non-cellulosic matter.
4.	6	90	135	29.33	Mild NaOH with high temp and medium time preserved cellulose integrity with decent whiteness suitable for eco-friendly extraction.
5.	12	90	135	30.23	strong purity and bleaching efficiency; slightly lower yield than top performer, but excellent for high-end applications like packaging or biomedical use.

The best yield (33.17%) came from 9% NaOH at 90 °C for 30 minutes, showing that short, high-temperature treatment works well. A similar yield (32.64%) was seen with 6% NaOH for a longer time (240 min). Higher NaOH (12%) gave good purity but slightly lower yield. Mild conditions (6% NaOH, 135 min) gave lower yield but were eco-friendly. Overall, the results show that the best conditions depend on whether the goal is high yield, purity, or sustainability.

5.2 Acid hydrolysis

Acid hydrolysis is a widely employed technique for extracting cellulose, cellulose nanofibers (CNFs), and glucose from various lignocellulosic biomass sources, including banana pseudo stem, wheat straw, sugarcane bagasse, and rice husk. This method selectively degrades the amorphous regions of cellulose while preserving or isolating crystalline domains, thereby enhancing properties such as crystallinity and thermal stability (Mohomane *et al*., 2022) [53]. Conventional processes typically utilize concentrated sulfuric acid, which is effective but can lead to cellulose degradation if not carefully controlled (Zhang *et al*., 2020) [55]. Consequently, recent research has emphasized optimizing hydrolysis parameters-such as acid concentration, temperature, and reaction time-to improve yield and reduce environmental impact (Almashhadani *et al*., 2022) [54]. For instance, in sugarcane bagasse, dilute acid hydrolysis (0.5–3% H_2SO_4) is commonly employed to convert cellulose into glucose, a key precursor for bioethanol production (Dussan *et al*., 2014) [57]. Additionally, eco-friendly alternatives, such as the integration of supercritical CO_2 treatment with mild acid hydrolysis, have emerged as sustainable options for CNF extraction, reducing chemical usage and processing severity (Mohomane *et al*., 2022) [53].

Optimization of hydrolysis conditions is also critical for accurately determining the crystallinity index of cellulose, a parameter essential for material characterization (Nelson & Conrad, 1948) [56]. The adaptability of acid hydrolysis across diverse biomass types underscores its relevance in both research and industry. Agricultural residues like banana pseudo stem and wheat straw have proven to be cost-effective and sustainable feedstocks for high-quality nanocellulose production (Almashhadani *et al*., 2022) [54]. Under moderate acid concentrations and controlled conditions, the process yields nanocellulose with enhanced crystallinity, dispersibility, and mechanical properties (Zhang *et al*., 2020) [55]. These attributes make the resulting materials highly suitable for applications in biodegradable packaging, nanocomposites, and biomedical devices. Thus, continuous advancements in acid hydrolysis techniques are pivotal in unlocking the full potential of renewable biomass for sustainable material development.

5.3 Ultrasound assisted extraction

The extraction of cellulose Fibers and nanofibers from lignocellulosic biomass using ultrasound-assisted chemical processes has emerged as an efficient and eco-friendly approach. Studies on banana pseudo stem have demonstrated that combining ultrasound with chemical treatments, such as alkaline or alkali-urea solutions, enhances delignification and disrupts complex cell wall structures (Freitas *et al*., 2022; Singh *et al*., 2020) [58, 62].

Ultrasound facilitates mass transfer, accelerates chemical reactions, and induces cavitation, which breaks down plant cell walls and promotes cellulose release (Poon *et al*., 2020) [61]. Typically, the process involves pretreatment with sodium hydroxide (NaOH) to remove lignin and hemicellulose, followed by ultrasonic irradiation to isolate cellulose nanofibers (CNFs) or high-purity cellulose fibers (Pappas *et al*., 2002) [60]. Particle size plays a crucial role; smaller particles offer a greater surface area, improving the effectiveness of both ultrasound and chemical agents, leading to increased yield and enhanced fiber quality (Liu *et al*., 2022) [59].

Following extraction, cellulose is washed, bleached, and dried to achieve high purity. Compared to conventional techniques, ultrasound-assisted extraction reduces chemical consumption, shortens processing time, and improves fiber properties, making it ideal for applications in bio-composites, hydrogels, and reinforcing agents (Liu *et al*., 2022; Poon *et al*., 2020) [59, 61]. Overall, this method provides a sustainable, scalable, and high-performance alternative for obtaining cellulose from plant biomass (Freitas *et al*., 2022) [58].

6. Applications of Extracted Cellulose

Extracted cellulose and its nanostructured forms such as cellulose nanofibers (CNFs), cellulose nanocrystals (CNCs), and bacterial cellulose have demonstrated wide-ranging applications across environmental, biomedical, material, and energy-related fields, owing to their biodegradability, high surface area, mechanical strength, and chemical modifiability (Klemm *et al*., 2011; Moon *et al*., 2011; Thomas *et al*., 2020) [1, 2, 3].

In environmental applications, cellulose-based materials are extensively used for wastewater treatment, air filtration, oil spill remediation, and soil detoxification due to their high adsorption capacity and modifiable surface properties (Lin & Dufresne, 2014) [4]. In the biomedical field, cellulose and its derivatives serve as wound dressings, drug delivery carriers, tissue engineering scaffolds, and biosensor components, attributable to their biocompatibility, non-toxicity, and ability to promote cell proliferation (Thomas *et al*., 2020) [3].

In polymer science, CNFs and CNCs function as reinforcing agents, enhancing the mechanical and barrier properties of biodegradable plastics and nanocomposites for packaging, coatings, adhesives, and 3D printing applications (Moon *et al*., 2011) [2]. Their roles as thickeners, stabilizers, and excipients in the food and pharmaceutical industries further underscore their multifunctionality (Nascimento *et al*., 2023) [24].

Beyond traditional applications, cellulose is increasingly integrated into energy storage systems. In supercapacitors and batteries, cellulose-based nanocomposites serve as electrodes, separators, and solid-state electrolytes due to their lightweight, porous, and thermally stable structure (Meng *et al*., 2019) [8]. Their compatibility with carbon-based nanomaterials and conductive polymers allows for the fabrication of high-performance, flexible, and eco-friendly energy devices (Lin & Dufresne, 2014; Thomas *et al*., 2020) [4, 3].

Moreover, cellulose contributes significantly to biodegradable packaging and bio-based textiles, supporting the transition toward a circular economy (Flores-Jerónimo *et al*., 2021) [23]. Its modifiability facilitates the development of advanced materials such as smart hydrogels and bioelectronics, expanding its utility into frontier technologies (Klemm *et al*., 2011) [1].

Overall, the adaptability and sustainability of cellulose continue to establish it as a cornerstone material across diverse sectors (Sango *et al*., 2018) [43].

6.1 Biofilms and biodegradable packaging

Biodegradable biofilms, made from natural biopolymers like starch, chitosan, gelatin, and cellulose from banana waste, are emerging as sustainable alternatives to petroleum-based plastics in food packaging. These biofilms are biodegradable, antimicrobial, and antioxidant, addressing the critical need for eco-friendly packaging solutions that reduce plastic pollution. Starch-based biofilms offer moisture resistance, while chitosan-based biofilms are enhanced with plant proteins such as those from Camellia oleifera residue, improving their mechanical strength and antimicrobial properties. The incorporation of gelatin and lignocellulosic biowastes into biofilms also provides active protection, inhibiting microbial growth and oxidation, which extends the shelf life of food products. Additionally, the valorization of banana waste (such as pseudostems and peels) for biofilm production exemplifies the use of agricultural byproducts as renewable resources for sustainable packaging (Sánchez-González *et al*., 2011; Zhao *et al*., 2020; Bajpai *et al*., 2019) [7, 9, 5].

These biofilms not only offer environmental benefits but also provide functional packaging with specific properties like moisture control, oxygen barrier qualities, and mechanical strength, making them highly suitable for food preservation. biofilms and biodegradable packaging serve as eco-friendly, low-cost solutions to extend the shelf life of fruits and vegetables while reducing reliance on synthetic packaging materials Hanumantharaju *et al*. (2022) [65]. biofilms and biodegradable packaging offer sustainable alternatives to conventional plastics by utilizing natural polymers to create eco-conscious, edible packaging materials. Chaitradeepa *et al*. (2024) [64] The addition of natural antimicrobial agents like eugenol and thymol further enhances their ability to reduce microbial contamination, addressing food safety concerns while maintaining biodegradability (Soleimani *et al*., 2019) [8]. By transforming lignocellulosic waste and banana byproducts into biofilms, this approach aligns with circular economy principles, converting agricultural waste into valuable, eco-friendly materials. This combination of sustainability and functionality makes biodegradable biofilms a promising innovation in the development of responsible food packaging systems (Mohammad *et al*., 2020) [6].

In addition to conventional uses, cellulose-based materials are rapidly advancing in cutting-edge biomedical technologies. Notably, nanocellulose which includes cellulose nanofibers (CNFs) and nanocrystals (CNCs) has shown immense promise as a carrier in targeted drug delivery systems. These nanostructures can be functionalized to deliver drugs directly to specific tissues or cells, particularly in cancer therapy, thereby reducing systemic toxicity and improving treatment efficacy (Zhao *et al*., 2017) [9]. Moreover, cellulose-based scaffolds are being developed using 3D printing technologies to fabricate personalized implants for tissue regeneration, offering a tailored approach for repairing complex injuries and defects. Emerging research also highlights the potential of cellulose nanocrystals as vaccine carriers or adjuvants, capable of enhancing immune responses and improving vaccine stability paving the way for improved immunotherapies and infectious disease management. Additionally, the development of smart wound dressings that integrate sensors and controlled-release systems into cellulose matrices could revolutionize chronic wound management by detecting infection markers and delivering therapeutics in real-time. These innovations, supported by cellulose's natural abundance, tunable properties, and eco-friendliness, make it a highly attractive material for future biomedical and pharmaceutical innovations.

6.2 Food industry applications

Cellulose, a natural polysaccharide abundantly available in plant biomass, is increasingly being extracted from agricultural and food industry wastes for value-added applications. Its functional versatility, biodegradability, and non-toxic nature make it an ideal ingredient in various sectors, particularly in the food industry. Extracted cellulose and its derivatives such as carboxymethyl cellulose (CMC), microcrystalline cellulose (MCC), and cellulose nanocrystals (CNCs) play critical roles in improving food texture, stability, shelf life, and nutritional value (Kamide, 2005; Khalil *et al*., 2012) [12, 15]. In food formulations, cellulose is widely utilized as a texturizer and thickener, enhancing mouthfeel and viscosity in sauces, dressings, dairy products, and bakery items (Kamyab *et al*., 2021) [13]. It also acts as a fat replacer in low-fat and calorie-reduced foods, offering creaminess without added fats (Wichchukit & O'Mahony, 2015) [19]. As a stabilizer and emulsifier, cellulose helps maintain emulsion stability, preventing phase separation in products like salad dressings and beverages (Yadav *et al*., 2019) [20]. Moreover, cellulose serves as a dietary fiber supplement, boosting the fiber content in functional foods such as cereals and baked goods (Miao *et al*., 2016) [18]. It is also used in the development of edible films and coatings, which act as biodegradable barriers to moisture and gases, thereby extending the shelf life of fresh produce and meat products (George & Siddaramaiah, 2012) [11]. In addition, encapsulation technologies employ cellulose as a carrier for bioactive compounds such as flavors, probiotics, and vitamins allowing for controlled release and improved stability (Matos *et al*., 2021) [17]. In beverage processing, cellulose functions as a clarifying agent, helping to remove suspended particles in juices, wines, and beers (Azeredo, 2009) [40]. Certain forms of cellulose also exhibit prebiotic potential, promoting gut health by supporting the growth of beneficial microorganisms (Lattimer & Haub, 2010) [16]. The advancement of cellulose nanostructures, particularly CNCs, has enabled the development of active and intelligent food packaging with antimicrobial and antioxidant properties (Kargarzadeh *et al*., 2018) [14]. Overall, the use of cellulose extracted from food and agricultural waste not only enhances food quality and functionality but also aligns with current trends in sustainability, clean-label ingredients, and circular economy practices.

7. Conclusion

The banana pseudo stem, a widely available agricultural byproduct, presents a valuable and sustainable source of cellulose with significant potential in various eco-friendly applications. This review has underscored the effectiveness of different extraction methods alkaline treatment, acid hydrolysis, and ultrasound-assisted techniques in isolating high-purity cellulose from banana pseudo stem. Among these, ultrasound-assisted methods offer notable advantages, including enhanced efficiency, reduced chemical usage, and improved fiber properties, making them particularly promising for sustainable processing. The mechanical, thermal, and biodegradable properties of the extracted cellulose demonstrate its suitability for applications in food packaging, biocomposites, and medical materials, offering an environmentally safe alternative to synthetic polymers. However, challenges such as inconsistent yield, high energy consumption, and lack of standardized procedures remain. Future research should prioritize the development of greener, low-impact extraction technologies, such as enzymatic and deep eutectic solvent-based methods, and explore the functionalization of cellulose for advanced applications like drug delivery systems and water purification. Moreover, industrial-scale implementation requires thorough assessment of economic feasibility and environmental impact. Overall, the valorization of banana pseudo stem not only contributes to waste reduction and sustainable material development but also supports global efforts toward a circular and bio-based economy.

Furthermore, the continued exploration of banana pseudo stem as a renewable resource for cellulose extraction aligns with global efforts to reduce reliance on fossil-based materials and mitigate environmental pollution. As research progresses, refining extraction methods to increase yield, purity, and cost-effectiveness will be key to unlocking its full potential. The diverse applications of banana-derived cellulose in industries such as packaging, construction, and biomedicine highlight its versatility and promise as a sustainable material. Additionally, integrating banana pseudostem valorization into circular economy frameworks could significantly contribute to resource efficiency, waste reduction, and the creation of green jobs in agricultural and industrial sectors. Future studies should focus on optimizing extraction conditions, investigating the scalability of production processes, and assessing the long-term environmental benefits of widespread adoption of banana-based cellulose materials. This will not only provide new avenues for utilizing agricultural waste but also foster a more sustainable and circular approach to material production.

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