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REVIEW

Coconut husk: A sustainable solution for eco-friendly packaging applications

Azime Özkan Karabacak[1,2] · **Özge Süfer**[3] · **Ravi Pandiselvam**[4,5]

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Abstract

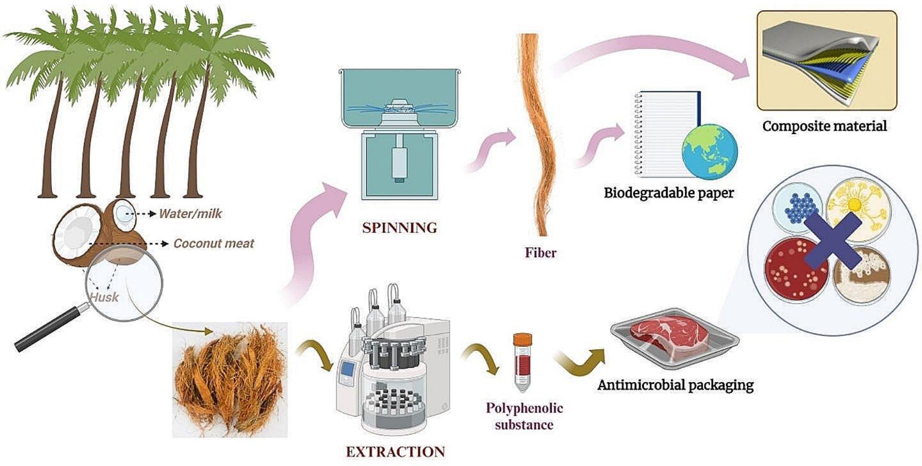
This paper explores the use of coconut husk as an eco-friendly alternative for packaging. It details the composition, extraction, and processing techniques of coconut husk, emphasizing its abundance and sustainable sourcing methods. Key findings include the use of polyphenols extracted from young coconuts, achieving an 81% reduction in CO_2 gas permeability and a 79% reduction in oxygen transmittance rate, demonstrating significant antimicrobial properties. The study highlights the creation of eco-friendly paper from coconut husk fibers and the development of bioplastics. Biocomposite films derived from coconut coir showed enhanced tensile strength and elongation, outperforming starch-based films. Environmental benefits include waste reduction and sustainable resource utilization, with the inclusion of 3% coir cellulose nanofibers in composite films notably improving tensile strength, elongation at break, and thermal stability. To sum up, this document highlights the importance of adopting sustainable materials in packaging and explores exciting possibilities for future studies, advancements in technology, and the widespread adoption of packaging solutions derived from coconut husks. This emphasizes the potential to drive a more environmentally friendly, sustainable, and eco-conscious packaging sector.

Highlights

- Coconut husk, a by-product, provides an eco-friendly alternative for packaging materials.
- Key findings highlight its potential in packaging with antimicrobial coatings, biodegradable paper, composites, and bioplastics.
- Rich in polyphenols, coconut husk offers a sustainable alternative to synthetic antimicrobials.
- Coconut husk packaging minimizes environmental impact, urging adoption in the industry.
- Abundance and versatility make coconut husk ideal for industry and the environment.

Extended author information available on the last page of the article

Graphical abstract



Keywords Coconut · Coconut husk · Packaging · Biodegradability · Eco-friendly

Nomenclature

CMC	Carboxymethyl cellulose
CFB	Coconut fiber reinforced bioplastic
CHB	Chitin reinforced bioplastic
CHF	Coconut husk fibers
CNF	Cellulose nanofibers
CRF	Coconut residue fiber
CST	Corn starch
EECH	Ethanolic extract of coconut husk
MAP	Modified atmosphere packaging
MW	Microwave
PA	Polyvinyl alcohol
PLA	Polylactic acid
PE	Polyethylene
PHcBV	Poly 3-hydroxybutyrate-co-3-hydroxyvalerate
SC	Sepiolite clay
TVB	Total viable bacteria
UV	Ultraviolet

1 Introduction

The unchecked increase in the utilization of plastic has resulted in an unparalleled volume of diverse plastic refuse to infiltrate the environment without any form of regulation. Approximately 50% of the worldwide aggregate plastic waste can be attributed to packaging plastics, with food packaging being the most prevalent. A significant portion of food packaging is intended for one-time use and is promptly discarded, thereby polluting the land, water, and the entire food supply chain. It is imperative for the food industry to adopt practices that minimize, reutilize, and recycle packaging materials, while also embracing a comprehensive approach to waste management in order to achieve a circular economy (Ncube et al., 2021). Green nanotechnology provides a sustainable avenue for the production of nanoparticles by minimizing their toxicity and harnessing biological resources. By incorporating principles from both green chemistry and engineering, this approach seeks to produce nanoparticles in a safe and environmentally friendly manner, eliminating the need for hazardous chemicals. Consequently, this has the potential to revolutionize nanoparticle manufacturing across multiple sectors of the economy (Nasrollahzadeh et al., 2019). For instance, *Ficus carica* extract (Zinatloo-Ajabshir et al., 2020), and grape juice (Zinatloo-Ajabshir et al., 2019) were used for eco-friendly/green synthesis of nanoparticles. Also, some other examples of this beneficial application are nanostructures (Zinatloo-Ajabshir & Salavati-Niasari, 2016; Ghodrati et al., 2020; Tabatabaeinejad et al., 2021; Zinatloo-Ajabshir et al., 2024), nanocomposites (Zinatloo-Ajabshir & Salavati-Niasari, 2019), and nanoplates (Hosseinzadeh et al., 2023).

On the other hand, in contemporary times, the utilization of agricultural waste has been widely acknowledged, due to the potential for environmental pollution resulting from inadequate management practices. Specifically, the improper disposal methods of coconut waste, namely the dumping and incineration of coconut husks and shells, contribute to environmental degradation. Consequently, scholars are currently directing their attention towards exploring the potential of utilizing coconut waste as a means of generating valuable secondary products. Among the prominent by-products that can be derived from this waste material are coir products, activated charcoal, biofuel, a filler for polyester composites, and concrete composites (Arun et al., 2022; Miyashiro et al., 2020; Ramesh & Radhakrishnan, 2019, 2022; Shruthy et al., 2021).

There are several different products that can be made from tender coconuts, including a unique treat called a snowball and a pentagonal-shaped, trimmed tender coconut. Additionally, coconut water is a popular product that can be enjoyed on its own or used as an ingredient in various frozen delicacies and ice creams made from coconut pulp. In addition to these treats, there are also refreshing beverages that can be made from tender coconut water, as well as flavored beverages, jams, jellies, and crispy tender coconut chips. However, before any of these products can be made, it is necessary to remove the husk of the tender coconut. This can be done either manually or with the help of machinery. Interestingly, researchers have discovered that, the weight of the tender coconut husk accounts for around 85% of the fruit's total weight (Ishizaki et al., 2008; Manikantan et al., 2018; Pandiselvam et al., 2020a). Every year, the coconut biomass, specifically the coconut husk, produces an astounding 6 million tons of waste. The husk, being the thickest part of the coconut, accounts for about a third of the fruit's overall biomass. Both mature coconut husks and young coconut husks possess a significant amount of lignocellulosic polymer, which contributes to their strength and durability. Unfortunately, this biomass takes a staggering nearly 9 years to decompose naturally, resulting in detrimental effects on the environment through methods such as open burning or soil contamination (Anuar et al., 2018; Din et al., 2021; Tooy et al., 2014; Tun et al., 2019). The coconut industry presents a remarkable opportunity for harnessing the abundant coconut husk biomass, which is able to be ingeniously utilized for both industrial and environmental endeavors. The transformation of coconut husk biomass holds immense potential for creating exceptional value (Ajien et al., 2023). For example, coconut peat and bagasse can be used as fillers in asphalt mixtures in order to prevent moisture damage (Wuttisombatjaroen et al., 2023). According to the Food and Agriculture Organization (FAO), Indonesia was the leader country in the production of coconut (17.2 million metric tons), and the Philippines and India followed Indonesia with the amounts of 14.7 and 14.3 million tons, respectively, in 2021 (Fig. 1A) (FAO, 2021). On the other hand, Fig. 1B demonstrates studies focused on coconut published in Science Citation Index Expanded (SCI-E) and Emerging Sources Citation Index (E-SCI) between 1976 and 2024, and the USA and Brazil depicted the best performances. However, among 20,018 coconut papers, only 7.54% belonged to coconut husk (webofscience.com/wos/woscc); therefore, this limited number should be increased. The mishandling of coconut husk biomass through improper disposal and open burning not only results in the wastage of valuable green energy but also poses serious threats to human health, the environment, and the overall balance of our planet. The detrimental effects include pollution, the amplification of greenhouse gases, the alarming rise in global temperatures, and the undeniable consequences of climate change. As a result, there is a pressing need for an alternative approach to managing coconut waste (Ajien et al., 2023; Ferronato & Torretta, 2019).

It is imperative to conduct a thorough and all-encompassing research study on coconut husk to compile and distribute the abundant knowledge about its viability as an environmentally friendly option for packaging. In light of the growing worldwide focus on sustainable methods, and the mounting environmental issues associated with conventional packaging materials, undertaking such a review would shed light on the various uses and ecological advantages of employing coconut husk for packaging purposes. Therefore, this article aims (i) to provide a holistic exploration of the various potential innovative uses of coconut husk, extending beyond its conventional applications. By exploring areas such as reinforcing fibers, it presents a fresh outlook on the multifaceted nature of coconut husk as a valuable asset; (ii) to investigate the properties and composition of coconut husk, and the processing and extraction methods used to harness its potential. By delving into these aspects, the article seeks to provide a comprehensive understanding of the material itself; (iii) to explore the applications of coconut husk in packaging, including antimicrobial coating, biodegradable paper, composite development, and bioplastic production. This novel approach offers a promising solution to waste management and promotes environmental sustainability; (iv) to emphasize the ecological consequences of the underutilization of coconut husks and the potential environmental benefits. An environmental impact assessment will be conducted to elucidate these benefits.

An all-encompassing examination would not only highlight the importance of adopting sustainable materials for packaging but also stimulate additional investigation, ingenuity,

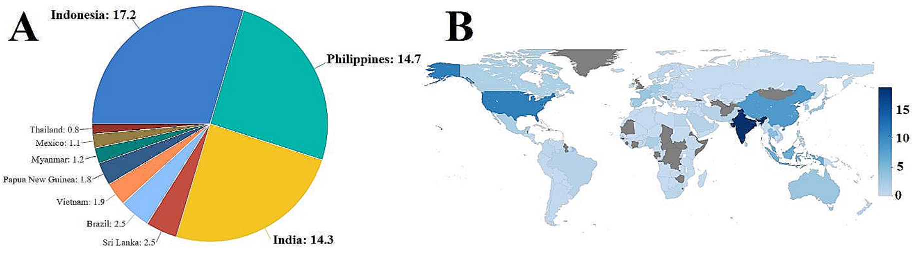


Fig. 1 Coconut statistics, (**A**) Leader coconut producers (million metric tons), and (**B**) Coconut studies (%) according to Web of Science Database

and implementation of packaging solutions derived from coconut husks. This would contribute to the progression of a more environmentally friendly and conscientious packaging sector.

2 Properties and composition of coconut husk

The tropical and subtropical zones are teeming with an abundance of coconut husk, a waste product rich in cellulose and lignin. Despite the potential for using coconut husk, there are significant challenges in efficiently and selectively converting it into valuable chemicals. This is mainly due to its unique and stable structure, which combines both cellulose and lignin components (Ding et al., 2018).

Coconut husk is a tough, fibrous material that surrounds the fruit. It is made up of both the inner endocarp and the outer mesocarp. The mesocarp is made of fibrous strands and cork-like cells that hold the fibers together. Soaking the husk in water helps separate the tough outer layer from the softer, fibrous part. The fibrous strands are strong and rigid, while the non-fibrous cells, called coconut pith, make up a significant portion of the husk's weight. There are many different types of coconuts, each with variations in the quality and quantity of the fibers. The age of the husk is important for obtaining high-quality fibers, with almost ripe to ripe coconuts producing the best fibers (Mishra & Basu, 2020). Coconut fiber can be categorized into two main types: white and brown. The white fiber is derived from young green husks through a process called theretting, resulting in a soft, smooth, and highly flexible material. On the other hand, the brown fiber is obtained from fully ripened coconuts (12 months mature) without undergoing any retting process. When it comes to quality, the finest fibers are obtained from mature coconuts, while lesser quality fibers are sourced from either immature or over-mature nuts. Nonetheless, both types of fibers play an indispensable role in the manufacturing of various coconut-based products (Kadam et al., 2014).

In a study conducted by Suman and Gautam (2017), the carbon, nitrogen, hydrogen, sulfur, and oxygen levels of coconut husk were determined to be 47, 0.21, 6.07, 0.12, and 46.60%, respectively. The volatile matter content was 82.94%, while the ash level was recorded as 0.92%. Moreover, a comprehensive examination of the carbohydrate composition of the fiber demonstrated that approximately 33% of the cell wall is comprised of glucose, specifically in the form of cellulose, with an additional 12% consisting of xylose, the predominant constituent of the hemicellulose component. Conversely, coir pith displays a lower content of glucose, at only 16%. The influence of maturity on the chemical makeup of the husk is investigated, revealing a substantial augmentation in glucose (cellulose) levels while the relative proportions of other sugars remain relatively unchanged (van Dam et al., 2006).

3 Processing and extraction of coconut husk

The process of removing the husk from coconuts is a crucial step in the coconut processing industries. This was traditionally done using a chopping knife and crowbar. The technique involved forcefully impaling the coconut with a sharp point. To create a more efficient dehusking machine, it is essential to consider various physical properties of the coconut, such as weight, size, shape, husk thickness, moisture content, and density. The shape, thickness, and moisture content of the shell also impact the effectiveness and capacity of husk removal. Additionally, knowledge of the thickness of the outer layer, roundness, and the friction experienced during both stationary and moving states is invaluable in designing a machine that can efficiently remove this outer layer. Furthermore, the parameters of the coconut kernel, such as weight, thickness, density, and moisture content, play a significant role in designing machines for grating, pulverizing, slicing, and extracting milk from coconuts. Therefore, a thorough understanding of the physical properties of both young and mature coconuts is essential for successful post-harvesting operations (Pandiselvam et al., 2020b). The report published by Sakhare et al. (2022) examined the intricate details of coconuts, focusing on their structure, properties, and strength required to remove the fibrous husk using a special tool. The tool itself was crafted from structural steel, which contains a moderate amount of carbon ranging from 0.25 to 0.55% and takes a force of 114 N to peel off the coconut's fibrous husk. In terms of shear stress, the tool experienced a maximum value of 1.6539×10^6 and a minimum value of -1.7689×10^6 when extracting the husk. The total deformation of the coconut husk extracting tool had a maximum value of 6.9214×10^{-6} and a minimum value of -7.6904×10^{-7}.

The extraction of coir fiber from the mother fruit plays a crucial role in determining its suitability for various applications. The process of extracting the fiber requires careful handling to obtain a high-quality end product that can be further strengthened to create materials for diverse uses. The extraction methods for coir fiber involve a combination of manual labor and machinery, demanding significant attention and human resources to achieve the desired level of excellence. The resulting fiber possesses exceptional material properties, making it an outstanding choice, when compared to synthetic alternatives (Khan et al., 2022). Regarding delignification, there are several methods commonly used, including sulfite, Kraft, soda, aqueous ethanol organosolv processes, steam explosion, and enzyme treatments. These processes involve chemical reactions that effectively remove lignin from the raw material, leaving behind a purified substance (Carre et al., 2019). The delignification serves as a preliminary treatment for the bleaching stage, to eliminate or disrupt the lignin bonds within cellulose. This procedure facilitates the manipulation of lignocellulose by enhancing its structural accessibility, thereby facilitating the extraction of cellulose (Rahayu et al., 2022). Sandy et al. (2021) used the soda pulping method and stated the details of the related technique as follows: the coconut husk was reduced to a dimension of 1 cm and subsequently subjected to extraction using a solution containing 35% NaOH. The process was conducted at a temperature of 110 ºC, and the duration was 110 min. The resulting dark-colored liquid, referred to as black liquor, was then treated with sulfuric acid until reaching a pH of 2, resulting in the formation of a precipitate consisting of lignin. The obtained lignin was subsequently dried in an oven at a temperature of 50 ºC for 3 h. Moreover, in the aqueous ethanol organosolv process, conditions were declared as; temperature: 190 ºC, duration: 1 h, and ethanol: water = 65% (v/v), and this approach was applied after dilute sulfuric acid treatment with coconut husk by Carre et al. (2019). Elevated concentrations of acidic substances are recognized to generate undesirable hydroxymethylfurfural and give rise to corrosion issues (Carre et al., 2019). Tessera et al. (2023) maximized the efficiency of process variables through the application of response surface methodology, discerning their impact on the delignification process and the recovery of cellulose. The pre-treatment conditions were optimized with a desirability value of 0.828, achieved by subjecting the sample to a temperature of 150 °C, a contact time of 2 h, and a liquid-to-solid ratio of 15 ml/g. The sample was immersed in an aqueous solution containing 48% ethanol. The same statistical tool was also utilized by Marques et al. (2022), and exceptionally pure and superior-grade lignins were extracted from various raw materials, including coconut fiber, each showcasing distinct structural attributes. These lignins exhibited a remarkable p-hydroxyphenyl-guaiacyl-syringyl composition, boasting an astounding purity exceeding 86%. If ionic liquids are used in the extraction or conversion of coconut husk, contradictory results may arise. For instance, *N, N,N*-dimethylbutylammonium hydrogen sulfate was very helpful for the fractionation of lignin-rich coconut husk biomass (Anuchi et al., 2022), but the same outcomes were not reported for 1-ethyl-3-methylimidazolium chloride (Rambo et al., 2020).

Nanocellulose has emerged as a noteworthy nanomaterial in recent times, primarily attributed to its distinctive characteristics, such as its ability to be replenished and its sustainable nature. Alkali-acid hydrolysis and steam explosion were tried to extract cellulose from coconut husk fiber, and the alkali-acid hydrolysis method resulted in a cellulose content that was 1.8 times greater compared to the alternative method. The most favorable reaction condition for the production of nano-crystalline cellulose was achieved at a temperature of 50 °C, an acid concentration of 45 wt%, and a reaction time of 60 min, primarily attributed to the considerable cellulose content of 85.6% (Poornachandhra et al., 2022). Despite previous findings supported by Poornachandhra et al. (2022), the steam explosion method shows great potential and effectiveness as a hydrothermal pre-treatment technique for the extraction of lignocellulosic components from biomass. This procedure involves auto-hydrolysis, wherein acetic acid and H_3O^+ are released as catalysts, promoting the separation process. The rapid decompression resulting from this method leads to the breakdown of hemicellulose without causing significant hydrolysis of cellulose, resulting in the production of superior substrates for bioconversion. Moreover, this environmentally conscious approach does not necessitate the use of chemicals and prevents equipment corrosion, making it a sustainable and ecologically friendly alternative to traditional methodologies (Nascimento & Neto, 2021). On the other hand, supercritical fluids have been identified as a viable pre-treatment option for the breakdown of the lignocellulosic structure of plant-based materials, thus contributing to environmentally friendly technological advancements. Putrino et al. (2020) showed that the application of pre-treatment using supercritical CO_2 resulted in alterations in the composition of the coconut fiber, leading to an augmentation in its porosity, a decrease in the presence of phenolic compounds and waxes, as well as the relaxation of hydrogen bonds, thereby inducing delignification.

The valuable compounds (except lignin, cellulose, and hemicellulose, such as phenolics) were recovered from coconut husk by water (Wary et al., 2022), acetone-water (Rachmawaty et al., 2017), methanol (Irondi et al., 2017), and ethanol (Buamard & Benjakul, 2017a, b; Buamard & Benjakul, 2019; Buamard et al., 2017; Olatunde et al., 2020a; Rachmawaty et al., 2017; Singh et al., 2020), and ethanolic extraction was also combined with high pressure treatment (Buamard & Benjakul, 2018), modified atmosphere packaging (Olatunde et al., 2019b), cold plasma (Olatunde et al., 2020b, c) and enzyme (Vate & Benjakul, 2017). Agitated bed and ultrasound assisted extraction methods had the capability of obtaining colorants from husks as well (Rodiah et al., 2018). The ultrasound technique was also declared successful for obtaining candidate prebiotics from coconut husk, and its extract may be categorized as a prebiotic possessing the capacity to be utilized as a constituent of functional food, according to Tang et al. (2021).

4 Applications of coconut husk in packaging

The demand for environmentally-friendly packaging materials, such as biodegradable and bioplastics, is increasing as a result of growing environmental concerns. Biodegradables and biopolymers are being categorized and utilized in food packaging, with their advantages and disadvantages being deliberated. The strength, minimal water absorption, and durability of coir fiber are currently being investigated. Additionally, coconut husks are being explored as potential composite reinforcement and raw materials for the papermaking industry due to their availability and potential for eco-friendly food packaging. The utilization of natural fibers like coir fiber is gaining popularity in the packaging sector (Hamouda, 2021). In this section, antimicrobial coating, biodegradable paper, composite development, and bioplastic production from coconut husk were discussed.

4.1 Antimicrobial coating

The existence of microorganisms poses a substantial threat to various food products, such as cheeses, bakery products, meats, and poultry, resulting in their deterioration (Tas et al., 2019). Antimicrobial coatings play a crucial role in preventing the growth of microorganisms on the surface of packaged foods, thereby extending shelf life and ensuring product safety (Kumar et al., 2023). In antimicrobial packaging technology, the incorporation of artificial substances into the composition of biopolymers is a common practice. This approach is favored due to its ability to preserve substantial antimicrobial levels throughout storage and prevent any potential interactions with food constituents, such as lipids and proteins. However, the utilization of these synthetic additives is restricted because of certain limitations, thereby impeding their wider implementation. During the manufacturing process, synthetic polymers not only contribute to waste and high energy consumption but also degrade landfills. Additionally, concerns such as negative health effects, unregulated dispersion on food surfaces, and undesirable tastes further compound the issue (Manzoor et al., 2023). As a result, there has been a rise in the utilization of naturally derived antimicrobial substances sourced from plants, which have proven to be viable substitutes (Bahrami et al., 2019, 2020). One promising avenue is the development of antimicrobial coatings derived from coconut husk fibers. The inherent antimicrobial properties of coconut husk can be harnessed to create a protective coating for food packaging materials, helping to extend the shelf life of perishable foods. The unique composition of coconut husk, rich in compounds such as lignin, cellulose, and hemicellulose, provides a favorable environment for the incorporation of antimicrobial agents. Coconut husk extract contains phenolic compounds such as tannic acid, hydroxybenzoic acid, 4- ferulic acid, syringic acid, q-coumaric acid, and vanillic acid, which act as protein cross-linkers, making it suitable for antimicrobial coating applications (Buamard & Benjakul, 2017b). These phenolic compounds induce the formation of a complex matrix, thereby improving the water barrier property of films or nanocomposite films (Jafarzadeh et al., 2020; Gani et al., 2023).

Table 1 presents recent literature findings and focuses on applications of coconut husk in packaging as an antimicrobial coating. Studies have shown that extracts from coconut husk possess antimicrobial activity against a broad spectrum of microorganisms, including *Staphylococcus aureus, Escherichia coli, Listeria monocytogenes, Salmonella typhi* and other spp., *Pseudomonas aeruginosa, Vibrio parahaemolyticus, Shigella flexneri*, and total viable bacteria. By integrating these natural antimicrobial components into food packaging materials, the coconut husk-based coatings can potentially mitigate the risk of microbial contamination, ensuring food safety and reducing food waste. This innovative approach aligns with the growing demand for sustainable and eco-friendly packaging solutions in the food industry, offering a biodegradable alternative that also contributes to the preservation of food quality and safety. As research in this field progresses, the development of coconut husk-based antimicrobial coatings holds promise for enhancing the efficiency and sustainability of food packaging materials.

The effectiveness of antimicrobial properties can be modeled using a bacterial growth inhibition model.

$$N\left(t\right)={N}_{0}\times {e}^{-kt}$$

Where, $N(t)$ indicates the number of bacteria at time t, N_0 is the initial number of bacteria and k is the rate constant related to antimicrobial activity.

4.2 Biodegradable paper

The paper industry has faced criticism for cutting down trees to make paper products. Therefore, biodegradable paper holds immense importance due to its potential applications and environmental benefits. The renewability and biodegradability of paper make it a sustainable alternative for various uses, such as in flexible electronics, microfluidic analytical devices, and energy storage systems (Konwar et al., 2023; Lim et al., 2019; Zhao et al., 2021). Additionally, the use of biodegradable paper in packaging materials aligns with the industry's shift towards more sustainable and renewable materials, contributing to environmental sustainability (de Fátima Silva et al., 2022). Furthermore, the potential for paper to be coated with bioplastics further supports its role in substituting non-biodegradable polymers, thus reducing its environmental impact. The unique properties of paper, such as passive liquid transport and compatibility with various chemical and biochemical moieties, make it a promising platform for sensing applications and other devices. Moreover, the applications of different types of cellulose aerogels derived from paper have been introduced, indicating the versatility and potential of biodegradable paper in various fields (Long et al., 2018). Coconut husks can be considered a potentially valuable resource for the pulp and paperboard industry due to their abundant supply, biodegradability, environmentally friendly properties, and renewability (Jeetah & Jaffur, 2022).

Figures 2 and 3 indicate paper production steps from coconut husk, the physical characteristics of paper, respectively, and the applications of coconut husk in the biodegradable paper industry, as indicated in Table 2. Coconut husk, whether used as 100% biomass or in combination with other materials, has showcased its potential in paper production, offering strength, sustainability, and fire resistance (Basak et al., 2016; Jeetah & Jaffur, 2022). Treatment of different coconut husk varieties in the paper-making process revealed that, the Local Tall Yellow variety stands out due to its favorable anatomical and chemical properties, while other varieties still hold promise for applications such as fiber plate and cardboard production (Afrifah et al., 2022). Furthermore, the incorporation of tender coconut husk into cellulose-starch-based composite paper showed promising results, with robust interactions observed between starch hydroxyl groups and coconut husk cellulose, indicating suitability for biodegradable material production with a significant degradation rate within a short timeframe (Pandiselvam et al., 2024). The diversity of coconut husk varieties further expands their applications in the paper industry (Afrifah et al., 2022).

4.3 Composite development

Composite materials are a category of materials formed by combining two or more constituent materials that possess distinct physical or chemical properties, resulting in a material that exhibits distinct characteristics not found in its individual components (Obada et al., 2019). These materials are designed to exhibit enhanced mechanical, thermal, and electrical properties, making them suitable for a wide range of applications, including packaging. The scientific and industrial communities widely acknowledge the importance of eco-friendly materials, recycling, and reusing in response to the increasing need for alternatives to non-renewable resources (Andrew & Dhakal, 2022). Biocomposites derived from biofibers and biopolymers hold significant appeal due to their ability to exhibit the necessary properties and functionalities while remaining cost-effective. Significant progress has been made in the field of biocomposites with regards to the utilization of diverse raw materials, processing techniques, characterization methods, and applications. Biofibers, including a variety of plant-based materials such as coir, hemp, and rice husk, have garnered considerable attention as a possible substitute for synthetic fibers such as carbon and glass (Bhatia et al., 2019). The consideration of mechanical properties and permeability plays a crucial role in the selection of biocomposites for use in the food packaging industry. To quantify the reduction in CO_2 gas permeability and oxygen transmittance rate, the following equations can be used. P_{CO_2} and P_{O_2} represent the permeability rates for CO_2 and O_2, respectively:

$$P_{CO_2} = P_{CO_{2,0}} \times (1 - R_{CO_2})$$

$$P_{O_2} = P_{O_{2,0}} \times (1 - R_{O_2})$$

Where, P_{CO_2} and P_{O_2} are the initial permeability rates, R_{CO_2} and R_{O_2} are the reduction percentages (e.g., 0.81 for 81%).

Coconut husk, also known as coir, is a lignocellulosic fiber obtained from the mesocarp of the coconut fruit and has been explored as a potential reinforcement in composite materials for packaging applications. The incorporation of coconut husk in composites has shown promising results in enhancing the mechanical properties, such as flexural strength, of the resulting materials (Johar & Ariff, 2022). Al-Oqla's study (2023) presented a novel genetic programming tree model that was capable of predicting the mechanical properties of natural fibers. This prediction was based on the analysis of various inherent chemical and physical properties, including moisture contents, lignin, cellulose, hemicellulose, and the microfibrillar angle. The utilization of artificial intelligence in predicting the overall mechanical properties of natural fibers would alleviate the need for extensive experimental efforts and reduce costs. This advancement would greatly contribute to the development of improved green composite materials for a wide range of industrial applications. Additionally, coconut husk has been investigated for its potential to improve the thermal conductivity of composites, which is a crucial property for packaging materials (Ekpenyong et al., 2022). Furthermore, the utilization of coconut husk in composite development aligns with the growing

Table 1 Selected examples of applications of coconut husk in packaging as an antimicrobial coating

Serial numbers	Biomass sources	Antimicrobial test	Packaging application or storage period	Remarkable results	References
1	Coconut husk, rubberwood sawdust, and palm leaf base	*L. monocytogenes, S. aureus*, spp., and *E. coli*	A sachet packaging with antimicrobial properties was created by incorporating emulsions of lime oil or *Litsea cubeba* oil.	• Compared to alternative sources, coconut demonstrated superior efficacy in releasing essential oil (EO) emulsion against bacterial growth. • With its limited water absorption capacity, coconut rapidly absorbs EO emulsion in the initial stages, allowing for the use of lower EO concentrations to inhibit bacterial growth. • Therefore, coconut presents a promising alternative for creating innovative antimicrobial packaging designs using biocomposite materials.	(Parichanon et al., 2021)
2	EECH	*P. aeruginosa, E. coli, V. parahaemolyticus, L. monocytogenes* and *S. aureus*	• Slices of Asian sea bass were combined with EECH60 (60% ethanol extract). • Samples were kept at 4 °C for 0, 3, 6, 9, and 12 days on a polystyrene tray covered with shrink film.	• EECH exhibited a considerable antimicrobial efficacy against all the tested pathogens. • Sea bass treated with 400 ppm EECH60 extended shelf life to 9 days, compared to the control's 3 days. • EECH60 reduced lipid oxidation, inhibiting spoilage and pathogenic bacteria, thereby prolonging sea bass slice shelf life.	(Olatunde et al., 2019a)
3	EECH	Total viable bacteria (TVB), Psychrophilic viable bacteria, *Pseudomonas*, H_2S-producing bacteria, and *Enterobacteriaceae*	• Modified Atmosphere Packaging (MAP) gas mixtures; *(GM1)*: 60% CO_2/30% N_2/10% O_2 and *(GM2)*: 80% CO_2/10% N_2/10% O_2 • EECH and MAP applied of Asian sea bass slices stored at 4 °C.	• The microbial load of slices decreased under MAP regardless of EECH treatment, compared to the control (no EECH treatment, packed in air). • Slices treated with 200-ppm EECH and packaged under GM1, as well as those under GM2 without and with EECH treatment, showed TVB values below 6.0 log CFU/g at day 15. • The combination of 200-ppm EECH treatment and GM1 packaging extended the shelf life of Asian sea bass slices beyond 15 days at 4 °C.	(Olatunde et al., 2019b)
4	EECH	*S.aureus, E. coli, V. parahaemolyticus, L. monocytogenes*, and *P. aeruginosa*	Liposomal encapsulated EECH (LE-EECH), crafted with two lipid phase levels, incorporating a soybean phosphatidylcholine/cholesterol mixture at 4:1 mol ratio (60 and 80 µmol/ml), along with two EECH concentrations (1% and 2%), was developed.	• 60 µmol/ml lipid phase levels with 1% EECH concentration demonstrates promising outcomes by addressing the dark color associated with ECHE and enhancing its antibacterial properties. • These results contribute to the potential utility of liposomal encapsulation in optimizing the properties of bioactive compounds for various applications.	(Olatunde et al., 2019c)

Table 1 (continued)

Serial numbers	Biomass sources	Antimicrobial test	Packaging application or storage period	Remarkable results	References
5	Poly 3-hydroxybutyrate-co-3-hydroxyvalerate (PHcBV) and coconut fibers	*S. aureus*	Green composite sheets, comprising coconut fibers with weight contents of 1, 3, 5, and 10% and PHcBV were utilized to create novel packaging materials.	• The study demonstrates remarkable results by achieving antimicrobial functionality with low coconut fiber content (3%). • The utilization of coconut fibers as natural vehicles for entrapping extracts, combined with oregano essential oil, presents an innovative and sustainable approach to developing active packaging materials.	(Torres-Giner et al., 2018)

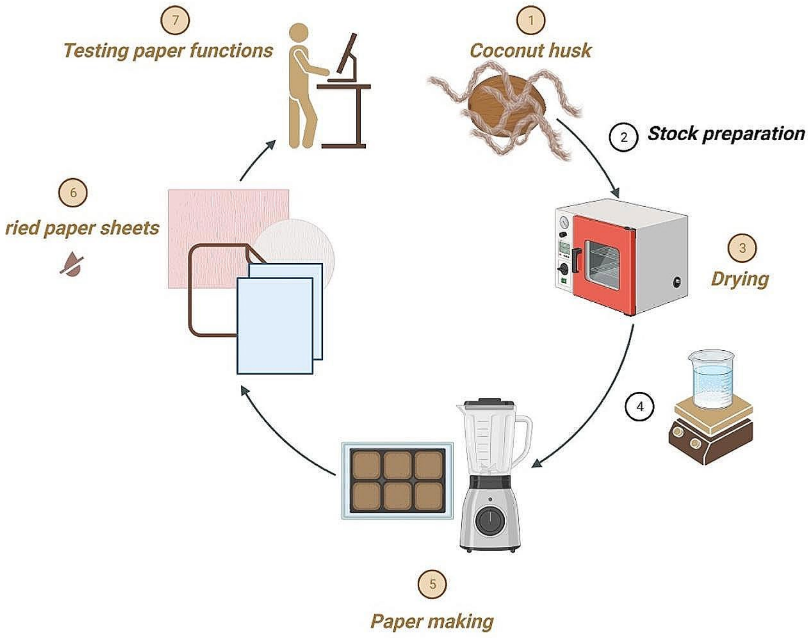


Fig. 2 Paper production steps from coconut husk (Adapted from Jeetah & Jaffur, 2022, and created with Biorender.com)

interest in environmentally friendly and sustainable packaging solutions, as coconut husk-based composites offer the potential to reduce the reliance on non-biodegradable materials (Ángel Hidalgo-Salazar et al., 2020). Therefore, the exploration of coconut husk in composite development for packaging applications presents an opportunity to create innovative and sustainable packaging materials with desirable properties.

Table 2 shows the significant findings on the utilization of coconut husk in composite production. The data highlights the diverse applications, including enhanced mechanical properties in biocomposites with varying coir ratios, improved thermal stability and resistance in CHF-reinforced biocomposites, and the promising potential of coconut-based nanocomposite films for sustainable food packaging (Kumar & Saha, 2022; Lekhasree et al., 2021). Thermal stability can be quantified using Thermogravimetric Analysis (TGA) data. T_{max} is the temperature at maximum degradation rate:

$$\Delta T_{max} = T_{max,composite} - T_{max,matrix}$$

Where, $T_{max, composite}$ indicates the maximum degradation temperature for the composite and $T_{max, matrix}$ indicates the maximum degradation temperature for the matrix.

Incorporation of coconut husk fibers in composite films and biocomposites has led to improvements in tensile strength, elongation at break, and surface hardness, making them

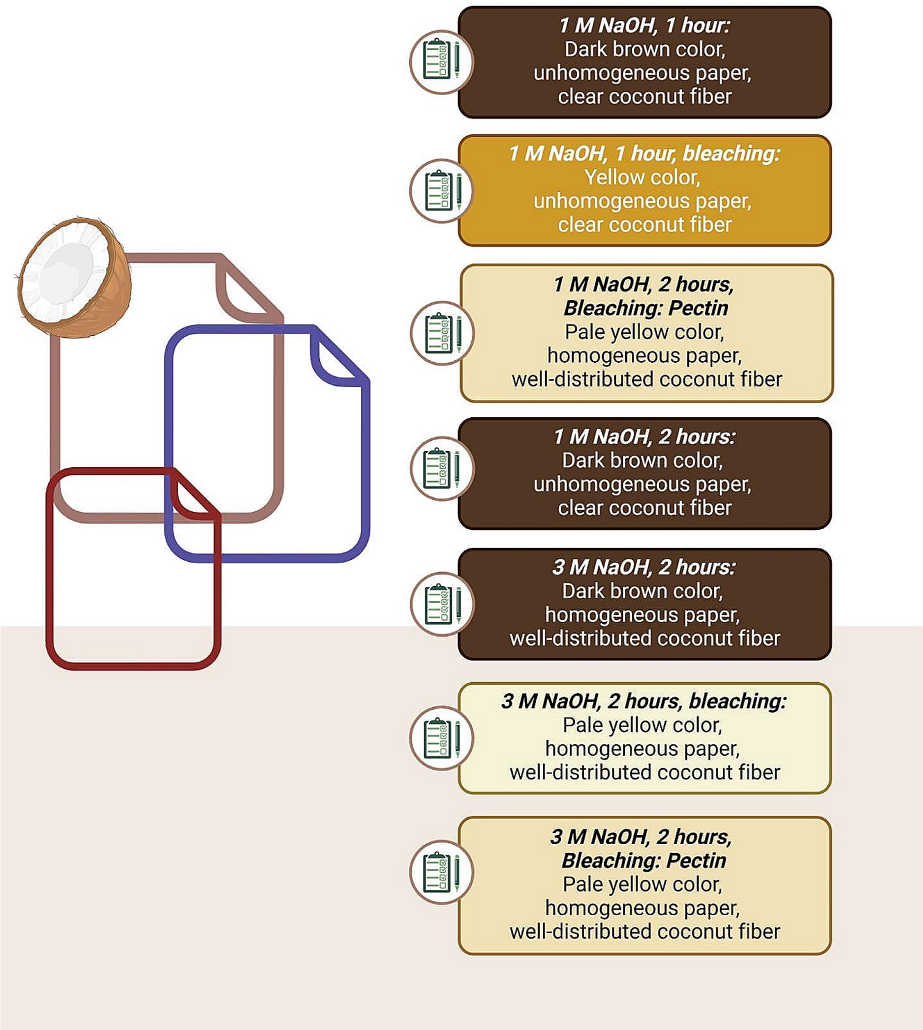


Fig. 3 Physical quality attributes belonged to papers made of coconut husk (Adapted from Bussaban & Chumee, 2019, and created with Biorender.com)

suitable for packaging applications (Gupta et al., 2022). For tensile strength (σ) and elongation (∈), the rule of mixtures for composite materials can be used:

$$\sigma_{composite} = V_f \sigma_f + V_m \sigma_m$$

$$\in_{composite} = V_f \in_f + V_m \in_m$$

Where, V_f and V_m are the volume fractions of the fibers and matrix, σ_f and σ_m are the tensile strengths of the fibers and matrix, $\in_f$ and $\in_m$ are the elongations of the fibers and matrix.

Table 2 Examples of various applications of biodegradable material from coconut husk

Serial numbers	Biomass sources	Biodegradable material	Process conditions	Remarkable results	References
1	Coconut husk	Paper	100% Coconut Husk 60% Coconut Husk + 40% Wastepaper 60% Coconut Fibers (unreinforced)	The reinforced 100% coconut husk paper exhibited impressive tensile and burst indexes, highlighting its potential as a strong and sustainable material.	(Jeetah & Jaffur, 2022)
2	Four varieties of *Cocos nucifera* husk: hybrid dwarf green, hybrid dwarf yellow, local tall green, and local tall yellow	Paper	Four coconut husk varieties were treated in the maceration process with a solution consisting of a 1:1 ratio of 30% hydrogen peroxide and 99.8% acetic acid.	• The local tall yellow stands out as a promising variety due to its favorable anatomical and chemical properties. • Despite limitations in the other three varieties, they still hold potential applications in fiber plate, rigid cardboard, and cardboard production, showcasing the diverse opportunities for utilizing different coconut husk varieties in the paper industry.	(Afrifah et al., 2022)
3	Tender coconut husk	Cellulose-starch based composite paper	Addition of potato and corn starch at 5%, 10%, and 15% ratios	• Decreasing trend in tensile strength with increasing starch concentration • No significant difference in moisture content between starch types • Robust interactions between starch hydroxyl groups and coconut husk cellulose observed via FTIR, XRD, and SEM analysis • Approximately 70% degradation rate within a 20-day period, indicating suitability for biodegradable material production	(Pandiselvam et al., 2024)
4	Coconut husk	Composite film	Composite films prepared from coir CNF and PA: • 1% CNF /PA • 3% CNF /PA • 5% CNF /PA	• Coir CNFs demonstrated enhanced characteristics, highlighting their potential as a reinforcing agent in biodegradable PA-based films. • The inclusion of 3% coir CNF, based on the dry film weight, notably improved tensile strength, elongation at break, and thermal stability in the composite films.	(Wu et al., 2019)

Table 2 (continued)

Serial numbers	Biomass sources	Biodegradable material	Process conditions	Remarkable results	References
5	Coconut fiber and wheat husk	Biocomposite	Biocomposites prepared from wheat straw, coconut husk and corn waste with following ratios: 1) 88:12:0 2) 73:9:18 3) 62:8:30 4) 53:7:40 5) 47:6:53	• After molding and heating, the sample 1 exhibited the highest tensile strength at 7 N/mm^2, attributed to the fibrous nature of coconut husk influencing tensile strength. • The intertwining of coconut husk fibers contributed to crack propagation, resulting in a stair-stepping stress-strain curve with a strain of 26%.	(Sharma et al., 2018)
6	Coconut coir and groundnut shell	Biocomposite film	Carboxymethyl cellulose (CMC) was produced by converting cellulose obtained from biomass sources such as coconut coir and groundnut shell. Biocomposite films 1) Coconut coir /Groundnut shell (CMC) 2) Starch and Coconut coir/Groundnut shell (CMC) 3) Commercial CMC	• These films outperform starch-based films, showcasing enhanced tensile strength and elongation. • Moreover, the use of water as a solvent and glycerol as a plasticizer contributes to both environmental sustainability and improved film properties, offering a promising avenue for eco-friendly packaging solutions. • The biocomposite film derived from sample 1 exhibits increased tensile strength and elongation.	(Gupta et al., 2022)
7	CHF	Nanocomposite film	Pectin combined with ZnO nanoparticles and CHF derived cellulose nanowhiskers were used to develop a nanocomposite. Green chilli fruit (*Capsicum sp.*) was chosen as a test sample.	• The nanocomposite films demonstrated remarkable improvements in tensile strength and elongation at break, coupled with effective antimicrobial properties that extended the shelf life of packaged food products. • Developed material provided a promising solution for enhanced and sustainable food packaging.	(Lekhasree et al., 2021)
8	CRF and Modified CRF	Biodegradable composite foam	CRF and modified CRF were incorporated into biodegradable composite foam at various concentrations ranging from 0%wt to 8%wt for CRF and from 0%wt to 6%wt for modified CRF.	• The inclusion of CRF at 2%wt modified CRF significantly enhanced mechanical properties. • The optimal synergy between 2%wt Modified CRF and 6%wt CRF resulted in improved moisture absorption, water stability, and well-suited properties for foam packaging applications.	(Nansu et al., 2021)

Table 2 (continued)

Serial numbers	Biomass sources	Biodegradable material	Process conditions	Remarkable results	References
9	CHF	Composite	• The surface of the CHF underwent a plasma treatment. • The composites of CHF reinforced with PLA were manufactured using the technique of commingled yarn.	• Plasma treatment of CHF in PLA green composites significantly improved interfacial adhesion, resulting in enhanced mechanical properties such as tensile strength and Young's modulus. • Despite similar morphological observations, plasma treatment effectively reduced the shrinkage of the composites with increasing fiber weight fraction, highlighting its potential in enhancing the thermomechanical properties of natural fiber-reinforced composites.	(Jang et al., 2012)
10	Coconut husk	Biocomposite	Biocomposite samples were obtained from five ratio of coirs: 1) 0% 2) 2.5% 3) 5.0% 4) 7.5% 5) 10.0%	• Incorporation of coconut particles significantly enhanced the mechanical performance of biocomposites, with sample 3 exhibiting superior tensile strength, flexural strength, and surface hardness compared to sample 1. • Sample 2 demonstrated higher impact strength, fracture toughness, and fracture energy, while sample 3 showed improved thermal stability and resistance to water, NaOH, and NaCl solutions.	(Kumar & Saha, 2022)
11	CHF and rice husk	Hybrid biocomposites	The combination of CHF and rice husk with PLA was achieved through melt mixing and hot press techniques, using fillers in ratios of 80:15:5 (R1), 90:5:5 (R2), and 98:1:1 (R3). Two different drying methods were applied: • Conventional oven drying at 60 °C for 24 h. • MW drying at a frequency of 2.45 GHz for 3 min.	• In comparing oven and MW treatments for different fiber compositions, oven-treated fibers with a R3 composition exhibited higher tensile strength (63 MPa), while MW-treated fibers demonstrated higher flexural strength (69 MPa). • MW treatment also enhanced the toughness of the bio-composites by at least 4% compared to plain PLA. • For the R1 composition, MW-treated fibers exhibited lower water absorptivity (2%) than conventionally treated fibers (5%), indicating improved water resistance.	(Johar & Ariff, 2022)

Table 2 (continued)

Serial numbers	Biomass sources	Biodegradable material	Process conditions	Remarkable results	References
12	Coconut husk	Carrageenan-based composite film integrated with carbon dots derived from lignin	Solvent casting technique after sodium hydroxide-based extraction of lignin from coconut husk	• Reasonable tensile strength (46.50 ± 1.32 MPa) with 27% increase in elongation at break • 70% UV-light blocking properties • 84% visible light transparency and 79% reduction in oxygen transmittance rate • 81% reduction in CO_2 gas permeability • Excellent antioxidant and antibacterial properties (against *E. coli* and *S. aureus*) • Practical application demonstrated with milk spoilage detection via noticeable color change in fluorescent emission	(Sangeetha et al., 2024)
13	Coconut husk	Bioplastic	A high-performance bioplastic was developed from coconut husk fragments using a resin-free approach involving partial lignin removal and hot-pressing.	• A resilient bioplastic with a tensile Young's modulus of 2.1 ± 0.4 GPa and tensile strength of 22.8 ± 4.4 MPa was successfully developed from coconut husk through a resin-free, delignification-based approach. • This green and cost-effective method not only enhanced mechanical properties, but also demonstrated excellent water stability and microbial biodegradability, showcasing the potential of lignocellulosic bioplastics for eco-friendly alternatives to petroleum-based plastics.	(Leow et al., 2022)
14	Coconut (*Cocos nucifera*) husk	Bioplastic	The use of coconut husk fiber as reinforcement in cassava starch-based bioplastics, with formulations ranging from 0–20% fiber content was investigated.	• Optimal results were achieved with 10% coconut husk fiber, showing improved tensile strength (0.68 MPa) and modulus of elasticity (4.9×10^6 N/m²), while further reinforcement up to 15% enhanced impact resistance, highlighting the potential of coconut husk as a sustainable and effective reinforcement material for bioplastics.	(Babalola & Olorunnisola, 2019)
15	Young coconut husk (*Cocos nucifera* L.)	Biodegradable plastics	Biodegradable plastics were synthesized from young coconut husk in Medan, Indonesia, modified with varying ratios of chitosan and glycerol.	• The increase in glycerol resulted in thinner, flexible plastics with higher degradation rates, while higher chitosan content produced thicker, less flexible plastics with slower decomposition in soil. • The physical characteristics, water resistance, and degradation percentages were influenced by the composition of chitosan and glycerol in the mixtures.	(Muchtar et al., 2023)

Table 2 (continued)

Serial numbers	Biomass sources	Biodegradable material	Process conditions	Remarkable results	References
16	Chitin and coconut fibers	Bioplastic	CST bioplastic was enhanced with 10 wt% chitin and coconut fibers, resulting in CHB and CFB.	• While CFB exhibited slightly higher tensile strength due to fiber stiffness, CHB displayed increased elongation at break with 5 mL glycerol concentration. • The findings suggest that optimizing filler concentrations and plasticizer proportions is crucial for enhancing the mechanical properties of CST bioplastics for potential applications in food packaging.	(Pradeep et al., 2022)
17	Paper waste and coconut fiber	Bioplastic	The ratios of waste paper and coconut fiber for composite fabrication, aiming to meet or exceed a 1 kg lifting strength threshold were optimized. Eco-friendly degradation measures were implemented to ensure the bio-packaging effectively breaks down in both freshwater and seawater environments.	• The development of bio-packaging from waste paper and coconut fiber composites, offered a lifting strength exceeding 10 N and successful biodegradation in both freshwater and seawater. • Community perception tests indicate that, overall, the bio-packaging is more appealing to the public than conventional single-use plastic, with the exception of strength considerations.	(Noor et al., 2020)

Additionally, the positive impact of plasma treatment on CHF-PLA composites, indicated enhanced interfacial adhesion and reduced shrinkage (Jang et al., 2012). MW drying in hybrid CHF and rice husk bio-composites demonstrates superior flexural strength and reduced water absorptivity, emphasizing the effectiveness of different processing techniques in optimizing material properties (Johar & Ariff, 2022). Additionally, the integration of coconut husk extracts, such as lignin-derived carbon dots, into carrageenan-based composite films has resulted in films with UV-blocking, transparent, and gas barrier properties, along with wide antioxidant and antibacterial functionalities, showcasing their potential for advanced packaging applications (Sangeetha et al., 2024). The comprehensive insights provided by Table 2 underscore coconut husk's versatility and efficacy in developing eco-friendly composite materials with enhanced performance characteristics.

4.4 Bioplastic production

Plastic is a substance composed of a diverse array of synthetic or partly synthetic organic compounds, possessing the ability to be easily shaped and formed into a variety of solid forms. Plastics are utilized in a vast and continuously expanding array of commodities owing to their extended lifespan and appealing attributes, such as cost-effectiveness, ease of production, adaptability, and impermeability to water (Babalola & Olorunnisola, 2019). From a chemical perspective, plastics are polymers with a significant molecular weight, usually consisting of approximately 1000 to 10,000 repeating units of monomers (Atiwesh et al., 2021). The environmental impact of traditional plastics is significant as a result of the increasing quantity of plastic waste that is accumulating in landfills and the natural environment, rendering plastic materials highly unsustainable. According to FAO, approximately 12.5 million tons of plastic products are utilized annually in the realm of plant and animal production, encompassing activities such as fisheries and forestry (FAO, 2023). To ensure the preservation of a sustainable environment for future generations, additional endeavors are required to transition towards the utilization of biodegradable plastics and decrease our dependence on traditional petroleum-derived plastics (Shen et al., 2020). Bioplastics have found application in diverse consumer goods, including, but not limited to, food containers, grocery bags, biodegradable cutlery, and food packaging. The primary benefits of bioplastics include a reduced carbon footprint and an improved ecological state with less pollution (Babalola & Olorunnisola, 2019). The high biodegradability of bioplastics plays a crucial role in mitigating environmental apprehensions associated with their use. Apart from their inherent characteristics, external factors such as temperature, oxygen and water availability, and microbial presence can also impact the biodegradability of bioplastics. For instance, the biodegradation rate of PLA in the natural environment outperforms that of polyethylene (PE), a commonly utilized material for producing a majority of plastic food and beverage packaging (Siddiqui et al., 2024). In a recent study by Meng et al. (2023), an assessment was conducted on the degradation mechanism of three commercially available bioplastics, namely starch, PLA, and polybutylene adipate terephthalate (PBAT), in diverse soil conditions. The degradation of bioplastics was observed to occur in two distinct phases. During the first phase (days 0–30), a significant reduction in weight (35.8–41.9%) was noted in the bioplastics, along with a notable rise in the soil's soluble organic carbon levels and an alteration in bacterial populations. The decrease in weight of the bioplastics observed during this phase can be attributed to the degradation of starch. During the second phase (days

30–360), there was a sustained but gradual decrease in weight and a gradual recovery of bacterial communities in the soil. This can be attributed to the gradual degradation of the remaining PLA and PBAT.

Although synthetic polymers are often labeled as biodegradable, their degradation typically occurs at a slow rate. Conversely, natural polymer-based bioplastics exhibit faster biodegradation kinetics compared to synthetic polymers. Lignocellulosic biomass represents a plentiful and sustainable plant-derived resource, primarily composed of cellulose, hemicellulose, and lignin. In contrast to petrochemical feedstock, which predominantly consists of C–C and C–H bonds, lignocellulosic biomass exhibits a significant abundance of carbon-oxygen bonds in its chemical composition. These distinctive structures have the potential to serve as innovative platforms for the development of functional polymers that are easily compostable or biodegradable (Ángel Hidalgo-Salazar & Salinas, 2019; Sánchez-Safont et al., 2018). Coconut husks, which are considered lignocellulosic biomass, consist of approximately 40% cellulose, 20% hemicellulose, and 30% lignin, exhibiting a composition similar to that of natural wood. In line with the zero-waste concept, coconut husk bioplastics present a viable alternative to synthetic plastic bags as packaging materials (Leow et al., 2022). The preparation steps for bioplastic made of coconut husk are shown in Fig. 4.

The recent literature findings indicated in Table 2 provide substantial evidence supporting the potential of coconut husk in bioplastic production, as it can serve as a source of biopolymers, biochar, activated carbon, cellulose fiber, and various other materials that can be utilized in the synthesis and enhancement of bioplastics. These studies demonstrate innovative approaches, such as resin-free methods and delignification-based processes, leading to the development of high-performance bioplastics with remarkable mechanical properties. The utilization of coconut husk fiber as a reinforcement material in cassava starch-based bioplastics and the synthesis of biodegradable plastics from young coconut husk with modified compositions highlight the versatility of coconut husk in tailoring bioplastic characteristics (Babalola & Olorunnisola, 2019). Furthermore, the enhancement of CST bioplastics with chitin and coconut fibers, as well as the optimization of waste paper and coconut fiber ratios for bio-packaging, emphasize the potential of coconut husk in creating sustainable and effective alternatives to traditional petroleum-based plastics (Pradeep et al., 2022). These findings collectively underscore the versatility and promise of coconut husk as a valuable biomass source for advancing eco-friendly bioplastic development.

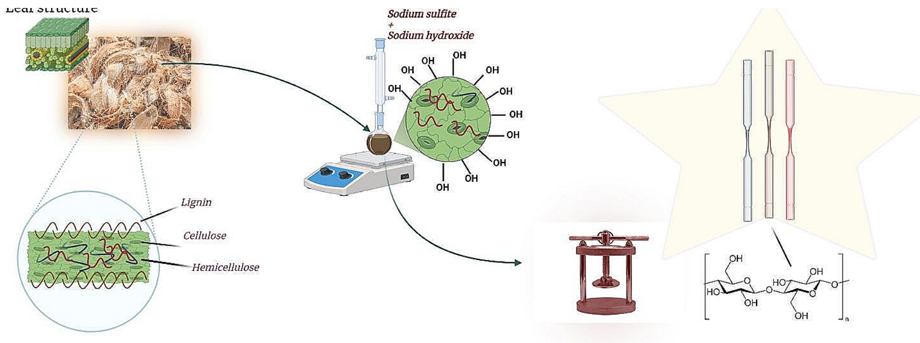


Fig. 4 Preparation steps of bioplastic from coconut husk (Adapted from Leow et al., 2022, and created with Biorender.com)

5 Environmental impact assessment

The environmental impact of food packaging has become a critical concern in the context of a circular economy, where the emphasis is on reducing waste and promoting sustainability. The use of coconut husk for food packaging aligns with these goals, as it offers the potential to minimize environmental impact and contribute to the efficient use of resources (Ajien et al., 2023).

Life cycle assessment (LCA) has been employed to evaluate the environmental impact of food packaging, considering factors such as production, use, and end-of-life disposal (Banerjee & Ray, 2022; Cristofoli et al., 2023; Usubharatana & Phungrassami, 2019). This approach is crucial for understanding the overall sustainability of packaging materials and identifying opportunities for improvement. Additionally, the importance of packaging functions in reducing food waste has been highlighted, as improvements in this area can contribute to achieving sustainability goals. The environmental impact can be assessed using a LCA approach, focusing on CO_2 reduction, waste reduction, and sustainable resource utilization. The overall environmental benefit (E) can be modeled as:

$$E = \sum_i w_i E_i$$

Where, E_i denotes the individual environmental benefits (e.g., CO_2 reduction, waste reduction) and w_i is the weights representing the importance of each benefit.

Furthermore, the potential for using coconut husk in the development of biodegradable and sustainable packaging articles has been explored, emphasizing the need for waste valuation and cost-effective solutions (Arena et al., 2016). Studies have demonstrated the potential for developing green composites, bioplastics, and biodegradable paper using coconut husk, contributing to the circular economy and bioeconomy (Arun et al., 2022; Jeetah & Jaffur, 2022; Leow et al., 2022; Muchtar et al., 2023). Furthermore, the utilization of coconut husk extract as an antimicrobial coating agent has been investigated, indicating its potential to maintain the quality and stability of food products during storage (Olatunde et al., 2019a; Parichanon et al., 2021; Torres-Giner et al., 2018).

The environmental impact of food packaging extends beyond its direct effects, as it is also linked to food waste and loss reduction. The interplay between packaging design, shelf life, and food waste has been recognized as a crucial aspect of environmental sustainability assessments. Additionally, the potential trade-off between reducing food losses and increasing environmental burden related to surplus packaging has been highlighted, emphasizing the need for a balanced approach in assessing the environmental impacts of food-packaging systems (Sánchez-Safont et al., 2018).

The application of coconut husk in food packaging aligns with the principles of a circular economy, as it represents a sustainable use of agricultural by-products and contributes to waste reduction. The potential for coconut husk to be used in the development of biodegradable packaging materials and its role in minimizing environmental impact across the supply chain have been emphasized in the literature. Furthermore, the environmental assessment of coconut husk-based packaging materials using LCA and the consideration of packaging functions in reducing food waste provide a comprehensive understanding of their sustainability implications (Cristofoli et al., 2023).

Consequently, the utilization of coconut husk for food packaging presents an opportunity to address environmental concerns associated with traditional packaging materials. By leveraging the sustainable characteristics of coconut husk and considering its potential to contribute to waste reduction and circular economy principles, it is possible to develop environmentally friendly packaging solutions that align with sustainability goals.

6 Conclusion and future prospects

The increasing global concern for environmental preservation has prompted investigations into alternative packaging materials, leading to a particular focus on coconut husk as a viable and eco-friendly solution. This review has comprehensively explored the composition, properties, extraction, and processing techniques of coconut husk, with a primary emphasis on its applications in packaging. Key findings highlight the potential of coconut husk in producing antimicrobial coatings, biodegradable paper, composites, and bioplastics, offering sustainable alternatives to conventional packaging materials.

The utilization of coconut husk, rich in polyphenols, exhibits considerable promise as a sustainable substitute for synthetic antimicrobial agents in food packaging. By harnessing the inherent antimicrobial properties of coconut husk, innovative coatings can be developed to extend the shelf life of perishable foods, thereby ensuring product safety and reducing food waste. Research indicates that coconut husk extracts contain phenolic compounds, such as tannic acid and hydroxybenzoic acid, which possess protein cross-linking properties, making them suitable for antimicrobial coating applications. These coatings not only prevent the growth of microorganisms on the surface of packaged foods but also contribute to enhancing the water barrier properties of packaging materials, thereby maintaining food quality over extended periods. Moreover, the incorporation of coconut husk into biodegradable paper presents an opportunity to enhance the resilience and endurance of packaging items while reducing their environmental impact. The renewability and biodegradability of coconut husk make it an attractive resource for the pulp and paperboard industry, offering strength, sustainability, and fire resistance. Whether used as 100% biomass or in combination with other materials, coconut husk has demonstrated its potential in paper production, aligning with the industry's shift towards more sustainable and renewable materials. The diverse applications of coconut husk in biodegradable paper production further underscore its versatility and efficacy in addressing environmental concerns associated with traditional paper manufacturing processes. Furthermore, coconut husk-based packaging materials exhibit a reduced environmental impact compared to conventional materials, presenting a compelling case for their adoption in the packaging industry. The abundance of coconut husk biomass, coupled with its versatility, provides a unique opportunity for harnessing this resource for both industrial and environmental purposes.The transformation of coconut husk holds immense potential for creating exceptional value, contributing to waste reduction and sustainable practices in the coconut industry.

The future prospects for coconut husk-based packaging materials lie in the continued refinement of extraction and processing techniques to optimize resource utilization, reduce carbon footprints, and enhance biodegradability. Furthermore, the development of coconut husk-based antimicrobial coatings, biodegradable paper, composites, and bioplastics offers sustainable alternatives to conventional packaging materials. These advancements align with the principles of a circular economy and contribute to waste reduction and sustainable practices in the coconut industry.

Moving forward, it is imperative to focus on addressing specific research gaps and identifying new contributions in the field of coconut husk-based packaging. This could involve innovative approaches to extraction and processing, novel applications of coconut husk in packaging, and the development of advanced materials with enhanced properties. Additionally, the environmental impact assessment of coconut husk-based packaging materials using LCA should be further explored to provide a comprehensive understanding of its sustainability implications.

By emphasizing the unique contributions and addressing specific research gaps, future research on coconut husk-based packaging materials can make significant strides in advancing sustainable and eco-friendly packaging solutions.

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Data availability Data will be made available on request.

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Authors and Affiliations

Azime Özkan Karabacak[1,2] · Özge Süfer[3] · Ravi Pandiselvam[4,5]

✉ Ravi Pandiselvam
anbupandi006@gmail.com; r.pandiselvam@icar.gov.in

Azime Özkan Karabacak
azimeozkan@uludag.edu.tr

Özge Süfer
ozgesufer@hotmail.com.tr

1 Food Technology Program, Gemlik Asim Kocabiyik Vocational School, Bursa Uludag University, Gemlik, Bursa, Türkiye

2 Science and Technology Application and Research Center, Bursa Uludag University, Bursa, Türkiye

3 Food Engineering Department, Osmaniye Korkut Ata University, Osmaniye 80000, Türkiye

4 Physiology, Biochemistry, and Post-Harvest Technology Division, ICAR-Central Plantation Crops Research Institute, Kasaragod 671 124, Kerala, India

5 Chemical & Biochemical Processing Division (CBPD), Central Institute for Research on Cotton Technology, Adenwala Road, Matunga (East), Mumbai 400 019, India