Sustainable
Food Technology

Accepted Manuscript

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View Article Online
DOI: 10.1039/D5FB00490J

## Sustainable spotlight

Cassava (*Manihot esculenta*) is recognized for its versatility and wide consumption across various regions globally. From cassava processing industries, a huge amount of cassava peels have been generated as agro-waste. These peels are valued for their rich content of starch, dietary fibre (cellulose and hemicellulose) and lignin, which can be utilized in various ways to reduce waste and provide additional economic and environmental benefits. This review primarily focuses on the extraction of cellulose, nanocellulose and starch from cassava peel. The review also provides a comprehensive overview of thermal, mechanical and barrier properties of various cassava peel derived biopolymer based composite films which is utilized in various packaging applications. The approach not only supports waste valorization but also contributes to environmental sustainability by replacing conventional synthetic packaging materials. Thus, the valorization of cassava peel into high-performance biopolymers presents a promising pathway towards eco-friendly and innovative packaging solutions that harmonize technological advancement with environmental sustainability.

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DOI: 10.1039/D5FB00490J

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[a*]Department of Food Engineering and Technology, School of Engineering, Tezpur university, Assam,784028

† The authors have contributed equally.

Supplementary Information available: [details of any supplementary information available should be included here]. See DOI: 10.1039/x0xx00000x

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

# A comprehensive review on the fabrication of cassava peel derived polysaccharides and its biocomposites for sustainable food packaging application

Nurin Afzia[a]†, Tabli Ghosh[a]†

## Abstract

From the past decades, agricultural waste derived sustainable packaging has received a considerable attention in the research and development section. The key motivating factor for agro-waste derived packaging is to mitigate the problems caused by fossil-based packaging, which creates a negative impact in the environment. Nowadays, cassava peel, an agricultural waste material has been extensively used as a natural source for the development of polysaccharides as starch, cellulose and nanocellulose. These polysaccharides can be used as a matrix or reinforcement in the design and development of stringent food packaging applications. Apart from this, the use of cassava peel-based polysaccharides has become one of the most utilized agricultural waste to waste management, with potential benefits for cassava processing industries. Thus, this review addresses the development of sustainable packaging materials from cassava peel derived biopolymers. Also, the review aims to discuss about the method used for the extraction of cellulose, nanocellulose and starch from cassava peel and some of the properties associate with these biopolymers. In addition, the review also summarizes about the applications and properties of thermal, mechanical as well as barrier properties of various cassava peel based composite films which is utilized in food packaging. The safety aspects and future outlook of cassava peel derived biopolymers for sustainable development has also been reviewed.

**Keywords:** Agricultural waste; Cassava peel; Polysaccharides, Sustainable food packaging.

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## Introduction

In the current sustainable developments, the environmentally benign materials have established a momentous interest in the 21st century due to the raising global population, rapid urbanization, and the desire for higher standards of living. This has emerged the central focus to the Sustainable Development Goals (SDGs),[1] as it addresses three of the most critical challenges that our world is facing today such as sustainable consumption and production (SDGs Goal 12), the fight against climate change (SDGs Goal 13), and the preservation of marine life (SDGs Goal 14). The design and development of sustainable packaging systems has also received a considerable attention from the past years.[2] Additionally, the fossil derived plastics has created an uncomfortable conundrum to the society with increased solid waste, carbon footprint, which in turn degrade the society in the recent past decades.[3] For years, the issue of plastic waste has emerged as a significant concern, primarily due to its excessive consumption, its resistance to decomposition, and its substantial contribution to negative impacts on landfills and water pollution.[4]

In the early 1800s, folding cartons were manufactured using paperboard and in 1850s, one of the recommended shipping containers *viz.* corrugated boxes has been developed.[5] The various plastics were discovered in 1800s such as vinyl chloride, styrene and cellulose nitrate, which were explored in the development of food packaging in later days.[5] Among available packaging materials, the plastic has been the most fascinating one since very early days, which create a huge number of solid wastes. In 2015, approximately half of plastic waste originated from single-use plastics, often used in packaging and designed for a one-time use before being discarded.[6] This fossil derived packaging material has raised a huge environmental pollution by generating greenhouse gas emission during production and disposal, while also consuming finite fossil resources. Food packaging alone represents about 50% of plastic derived from fossil fuels. Once discarded, such plastics persist in the environment for decades, gradually fragmenting into microplastics that can seep into the ecosystem and enter the food chain, leading to bioaccumulation. An effective approach to address this issue is the replacement of fossil derived polymer materials with biodegradable/renewable alternatives.[7] This approach aims to facilitate the decomposition of biodegradable materials with the aid of microorganisms, leading to a reduction in the ecological impacts.[4]

Various biomass obtained from agricultural residues, forestry residues, and urban miscellaneous waste are extensively valorised for sustainable food applications. As represented in **Fig. 1**, the agricultural residues include farm based, agro-industrial based and others. Farm based waste mainly generated at the time of crop cultivation which includes straw, husks and stalks. However, the agricultural wastes received from the cultivation and processing of agricultural products are potential sources for polysaccharides including starch, pectin, cellulose and nanocellulose. These waste streams are widely used as a raw material for the development of biopolymers. Moreover, agro-industrial waste materials including sugar cane bagasse, bamboo bagasse, mango bagasse, apple pomace, coffee husk/pulp, cassava, etc. are extensively utilized for various applications.[8,9] Utilization of these agricultural byproducts can also be transformed into biofiber and biopolymer materials, which can be employed for versatile food applications such as bioplastic packaging, disposable packaging, trays and food coatings, as well as long-lasting uses like plastic mulching, pharmaceuticals, medicinal products, and automotive components. Apart from this, forestry residue consists of logging wastes, including branches, bark and treetops, as well as wood processing byproducts such as sawdust and offcuts. Furthermore, urban miscellaneous waste covers municipal solid waste from the households and cities, livestock and poultry manure and other organic discards.

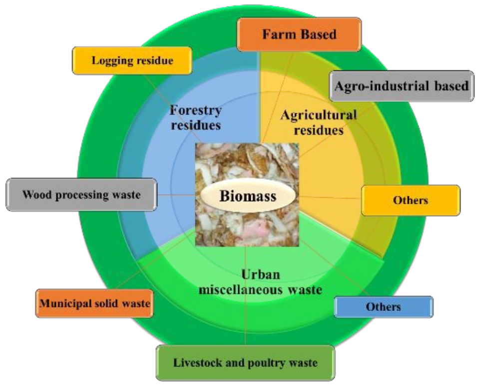


**Fig. 1** Various sources of biomass targeted for sustainable developments

Among these diverse residues, presently one of the important agricultural wastes which is used for the industrial purpose is cassava peel. Cassava (*Manihot esculenta*) is a versatile and widely consumed root vegetable found in various regions globally. In India, it is mostly cultivated in southern states of Tamil Nadu, Kerala, Andhra Pradesh and north-eastern states of Assam and Meghalaya. Cassava is well known for its starchy tuber, which can be used in various food applications. It is primarily valued for its starch content and cassava contains around 60-70% of starch on a dry basis. It also contains lignocellulosic components, including cellulose, hemicellulose, and lignin.[10] The production of cassava flour inherently generates by-products such as cassava wastewater (liquid waste) and cassava peels (solid waste). Cassava wastewater is obtained in the drying steps and contains a high percentage of organic compounds. On the other hand, cassava peel is indeed a lignocellulosic residue[11], comprising approximately 45% starch, 27% hemicellulose, 14% cellulose, 11% lignin, 10% crude fiber, and 3.5% protein. Moreover, use of cassava peel in sustainable food packaging is an innovative and eco-friendly approach to reduce waste and promote sustainability in the food industry. It can be used for preparing biodegradable films, bioplastics as well as biocomposites. Cassava peel extracts can be used

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as a natural preservative in food packaging. The antimicrobial properties of cassava peel can also help to prolong the shelf life of food products. Beyond the food sector, cassava peel can also be utilized as an organic fertilizer to enhance the soil fertility. Recent studies also highlighted the innovation approach of cassava peel in the field of acoustic material industry for the development of acoustic panels. Additionally, cassava peel has been explored in microbial fuel cells, where it serves as a supplementary energy source, contributing to renewable energy generation and improved energy efficiency. In the field of environmental management, cassava peel shows a sustainable coagulant aid in wastewater treatment. Collectively, these diverse applications emphasize the role of cassava peel valorization in advancing sustainability, resource recovery and bioeconomy practice.

Polysaccharides synthesized from cassava peel is one such sustainable alternatives to synthetic polymers. The cassava peel-based polysaccharides such as cellulose, starch, and nanocellulose can be extracted using chemical, mechanical and chemo-mechanical treatment. The extracted polysaccharides are utilized to develop biocomposites in combination with other polysaccharides for food packaging applications. Cassava peel-based polysaccharides can be processed into edible films and coatings that are used to extend the freshness of food products. These films can serve as barriers to moisture, oxygen, and other contaminants, helping to preserve the quality and freshness of perishable foods. They can be used as thickening, stabilizing

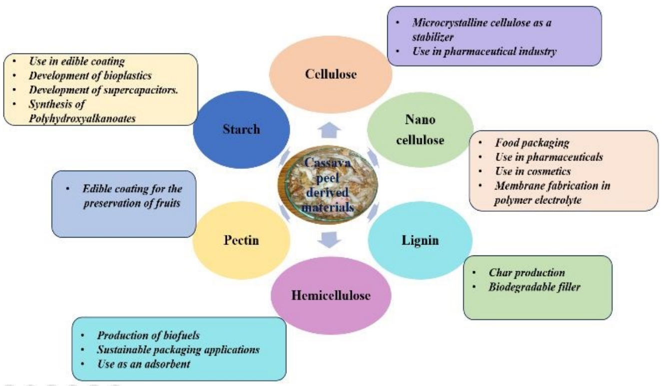


**Fig. 2** various cassava peel derived materials with their use

and gelling agents in various food products as represented in **Fig. 2**. The cellulose fraction can be converted into microcrystalline cellulose, which functions as a stabilizer and finds extensive use in the pharmaceutical industry. Its nanoscale derivatives (nanocellulose) exhibit superior mechanical and barrier properties, enabling their utilization in membrane fabrication for polymer electrolytes, food packaging, pharmaceutical carriers, and cosmetic formulations. Starch isolated from cassava peel has been exploited for the synthesis of polyhydroxyalkanoates (PHA), preparation of edible coatings, development of biodegradable plastics, and even in the design of energy-storage devices such as supercapacitors. Similarly, pectin derived from cassava peel serves as an effective edible coating, particularly for prolonging the shelf life of fresh fruits. Lignin, another important component, is employed in char production and as a biodegradable filler in polymeric composites. Hemicellulose, on the other hand, can be valorized into biofuels, sustainable packaging materials, and functional adsorbents for environmental applications. Moreover, cassava peel-based polysaccharides can be employed to encapsulate and protect sensitive food ingredients or bioactive compounds. Based on the discussion, the review demonstrates the strategical roadmap for the importance of cassava, fabrication of cassava peel derived polysaccharides and biocomposites for sustainable food packaging applications.

## Composition and uses of cassava and cassava peel

### Composition and uses of cassava

The chemical compositions of cassava may differ based on various factors including its variety, composition of the soil, environmental conditions, geographical locations, and the selected parts of the plant. In cassava, starch is found in higher concentration along with protein, fat, fibres, and minerals in lower concentrations. Additionally, the higher carbohydrate content in fresh cassava root makes them a good energy source.[12] Around 64-72% of the carbohydrate is found in the form of starch in cassava roots and the remaining includes sucrose, fructose, glucose, and maltose.[13, 14] Cassava roots consist of 32-35% carbohydrates on a fresh weight basis. In sweet cassava, sucrose content is found to be more compared to other varieties.[14] The majority of starch in cassava is stored in the amyloplasts region and the edible starch content in cassava roots can indeed vary depending on several factors, including the cassava variety, growing conditions as well as maturity of the roots. It ranges from 80% to 90% of the total weight of root. In the case of cassava leaves, the content of amylose can vary within a range of 19% -24%. The fiber content of cassava leaves also varies based on the variety and age of the cassava roots. In case of fresh cassava roots, the fiber content should be less than 1.5%. Moreover, the protein content of cassava root is relatively lower as compared to other starchy foods and it is around 1-3% on (dry weight) basis. Cassava contains a relatively low amount of fat, typically ranging from 0.1% to 0.3%. Although cassava has low overall fat content, but it consists of 45% of nonpolar lipids and 52% of different glycolipids, with galactose-diglycerides being predominant.[12] Cassava plants indeed offer a variety of essential nutrients, making them a valuable dietary resource, particularly in regions where they are used as a staple food for millions of people. Cassava roots are used in various ways across the globe due to their versatility and nutritional value. Grating cassava roots and pounding them into a pulp to make porridge is one of the traditional methods of preparing cassava in some regions.[15] Mingao and manicuera are two of the traditional Amazonian food products which are prepared from cassava. Fermented cassava is used for the preparation of mingao, whereas manicuera is prepared by using boiled cassava juice. Dumby is another food product which is

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prepared from boiled cassava root.[16] Fufu is one of the traditional cassava derived fermented foods of West Africa, which is prepared by crushing and sieving the fermented cassava and then cooking in water.[16] Apart from this, some other food products that are obtained from cassava are Gari, Lafun, Kpokpogari, Purupuru, and Peujeum.

Cassava has a wide range of industrial applications beyond its traditional use. It is widely used as ingredients in bakery products, extruded snacks, cereals and in biodegradable packaging materials, such as bags, containers, and utensils. There is a growing demand for alternative flours in the bakery industry due to various factors such as nutritional considerations, gluten intolerance, and wheat allergies. Cassava flour is indeed one of the options that have gained popularity as a substitute for wheat flour, especially in gluten-free and functional bakery products. Casabe, made from cassava flour, is a traditional type of bread in South America. It has a unique taste and texture, which can vary depending on the preparation method and regional variations.[17] One of the studies conducted by Chinma and Gernah in 2007 focused on the preparation of cookies using a composite of cassava flour, soybean, and moderately ripe mango fruits. The researchers created cookies with different proportions of these ingredients, ranging from 100% cassava flour to various combinations of cassava, soybean, and mango. They also used 100% wheat flour cookies as a control group for comparison. The study explored the use of a composite of cassava flour, soybean, and mango to create cookies with improved nutritional content.[18] The application of cassava starch in the production of edible food packaging has gained attention due to its biodegradability and versatility. In 2017, Piñeros-Hernandez has incorporated polyphenols-rich rosemary extracts into cassava starch films, leading to the development of active food packaging materials with antioxidant properties. The incorporation of rosemary extracts preserved the quality of the food and also maintain the biodegradability of the packaging materials.[19] In Thailand, plastic films have been produced from 100% cassava starch through a process called "annealing. These cassava starch-based films are extremely biodegradable, offering an eco-friendly alternative to traditional plastic films.[20] Further, cereal starch can also be used in the formation of sugar syrups and these sugar syrups can be used in various food and beverage applications.[21] Glucose syrups obtained from cassava starch can be used as sweeteners in the production of candies. In the pharmaceutical and detergent industry, cassava starch is used in different forms.[22]

Considering the rising demand of cassava peel and cassava-based products in food processing and packaging industry, it has been observed that this crop will maintain its significant contribution towards ensuring food security across the world. Cassava varieties cultivated across the world contains a natural toxic compound known as cyanogenic glycosides.[23] Cassava varieties are often described as being bitter or sweet by reference to the taste of fresh roots and this partly correlates with cyanogen concentrations.[24, 25] Bitter varieties are associated with high concentrations of cyanogenic glycosides (>100 mg/kg fresh weight) which causes various environmental issues such as drought, low soil fertility, pest attack, etc.[23] Sweet varieties have a high concentration of free sugars and low concentration of toxin content. Along with the raw cassava, cassava peel also contains cyanogenic glycosides particularly linamarin and lotaustralin, which is converted into poisonous hydrogen cyanide with the enzyme linamarase. Owing to this issue, any portion of cassava in its raw form can not be consumed and requires proper detoxification methods before consumption. Common methods such as drying, grating, fermentation, boiling, steaming etc. are used for the detoxification of cassava. Apart from the toxicological aspects, cassava also contains antinutritional compounds such as phytic acid, tannins, oxalate, nitrates and saponins. Phytic acid has strong ability to chelate minerals like iron, zinc, calcium and thereby reduce their bioavailability. Nitrates, on the other hand may lead to methemoglobinemia, whereas saponin disrupt the cell membranes, affecting nutrient absorption. Therefore, prior to the utilization of cassava or its peel as a food product or in packaging applications, these issues must be carefully addressed, and proper processing strategies need to be adopted for its safe and effective use.

## COMPOSITIONS AND USES OF CASSAVA PEEL

Cassava peel is considered as an important byproduct in cassava-based processes, which is utilized in various applications. It contains a significant amount of starch, dietary fibre (cellulose and hemicellulose), and lignin. The percentage composition of lignocellulosic biomass cassava peel has been represented in **Table 1** as reported by various researchers. Moreover, the protein content in cassava peel is generally low as compared to cellulose and starch and it is approximately 3.5-5.29%.[26] Cassava peel also contains 3-7% of ash, which includes various minerals such as calcium, potassium, and magnesium. Cassava peel also contains a significant amount of cyanogenic glycosides and it is found to be around 710.98 mg Hydrogen cyanide (HCN)/kg in unprocessed peel meal.[27] Now a days, cassava peel-based polysaccharides are widely used as a reinforcing agent in various packaging industries, so it is very much essentials to reduce the cyanide level from cassava peel otherwise it may cause cyanide poisoning. In this regards, proper soaking, drying and scraping can reduce the content of cyanide upto an acceptable level. Fermentation is also one of the techniques that is used to reduce the cyanide level to a safe level. In fermentation process, microorganisms are used to convert the cyanogenic glycosides into safer compounds like cyanohydrins, subsequently breaking them down into harmless byproducts such as ammonia.[28] The Food and Agriculture Organization (FAO)/World Health Organization (WHO) (1991) recommended the limit value for the safety of consumption of cassava products as 10 mg HCN/kg.

**TABLE 1.** Composition of cellulose, hemicellulose and lignin in cassava peel.



 

| SL no | Cellulose (%) | Hemicellulose (%) | Lignin (%) | References |
|---|---|---|---|---|
| 1. | 13.75 | 37.86 | 9.14 | [29] |
| 2. | 5.5-15 | 41-65 | 9-16 | [30] |
| 3. | 14.17 | 23.40 | 10.88 | [31] |
| 4. | 42.20 | 43.80 | 12.40 | [32] |
| 5. | 37.90 | 37.00 | 7.50 | [33] |
| 6. | 37.90 | 23.90 | 7.50 | [34] |
| 7. | 37.90 | 37.00 | 7.52 | [35] |
| 8. | 37.9 | 23.90 | 7.5 | [36] |

The cassava peel and bagasse can be utilized in various ways to reduce waste and provide additional economic and environmental benefits. In food packaging applications, cassava bagasse-based cellulose and starch can be widely used for the preparation of packaging films. Nanocellulose prepared from cassava bagasse is also used as a filler to enhance the mechanical properties, elasticity, and transparency of cassava-based films.[37] These films are used in the packaging of various food items including meat products. They also show a high activity towards microorganisms.[38] Cassava pomace is also considered as one of the good sources for packaging due to its high content of starch and dietary fibre.[39] Apart from this, cassava peel is used in animal feeding also due to its high energy source, nutritional value, and availability. Besides this, it is also used in fish and poultry feeding. Cassava peel is considered as a good dietary replacement for maize due to its low cost. In 2022, Aro et al. has conducted research on the microbial fermentation of cassava waste. This fermented cassava waste was then used as a dietary replacement for maize. This suggests that cassava waste can be repurposed as a feedstock or ingredient in animal feed or other agricultural applications, when the price of traditional cereal grains such as for maize is high.[40] Cassava peel, with its composition of cellulose, hemicellulose, and lignin can be used to prepare activated carbon. This approach is considered environmentally friendly and sustainable, as it repurposes agricultural waste (cassava peels) and reduces the need for more traditional sources of carbon materials.[29] In 2012, Adowei et al. conducted a study to compare the properties of commercial activated carbon and cassava peel derived activated carbon. From the study, it has been observed that activated carbon derived from cassava peel exhibits similar properties to that of commercial activated carbon.[41] Cassava peel is also considered as a good source of organic fertilizer, which is used to enhance the soil fertility.[42] Moreover, it is also used as a feedstock for the production of bioethanol.[43]

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Another research carried out by Thuppahige et al has observed the surface morphology of cassava peel, bagasse and commercially available cassava starch. As represented in **Fig. 3(a)**, the honeycomb-like and heterogenous chambers of the cassava peel has been observed. Each chamber is strongly enclosed by thick cell walls composed of sclerenchyma cells. Moreover, a significant amount of starch granules was also observed within the cassava peel. These starch granules were found to have round, irregular and are closely adhered to the cell walls. Morphological structure of cassava bagasse was also explained in the **Fig. 3(b)**. A thin and disordered arrangements was observed in case of cassava bagasse, which is associated with the vascular bundles. This vascular bundle is associated to the presence of fibrous structure of the cassava bagasse. Moreover, a large amount of round and irregular shaped starch granules is also observed in cassava bagasse. Furthermore, from the Scanning electron microscopy (SEM) analysis, it has also been observed that starch granules obtained from cassava bagasse and cassava peel shows the same morphology with the commercial cassava starch. Based on the SEM micrographs, it has been noted that the surfaces of the commercial cassava starch granules exhibit a smooth texture. Additionally, the chemical composition of cassava peels and bagasse were also analysed in this research. It has been observed that both peel and bagasse contain highest amount of carbon and oxygen. The other important mineral compounds such as Ca, Na, Fe, Al, Si etc are also present. The thermal property of cassava peel and bagasse has been studied using thermogravimetric analysis. Three stages of thermal decomposition have occurred in both the cassava peel and bagasse. The initial phase is related to the loss of mass due to the evaporation of water. In case of cassava peel, the loss in the mass was around 9.26% which in case of cassava bagasse it was 1.18%. Based on the findings, it has been observed that cassava peel shows higher moisture activity as compared to cassava bagasse. There was an additional thermal decomposition stage obtained for the peel, which was occurred in between 139.4 to 251.5 °C. The second decomposition phase associated with the degradation of starch was observed at 250 °C for cassava peel and 235 °C for bagasse. In the third decomposition stage, the mass loss of cassava peel was 25.28% which was slightly higher than cassava bagasse. The higher in mass loss also indicates the presence of more fibrous material in cassava peel. So, it can be concluded that both cassava peel and bagasse exhibit slightly different thermal properties.[44]

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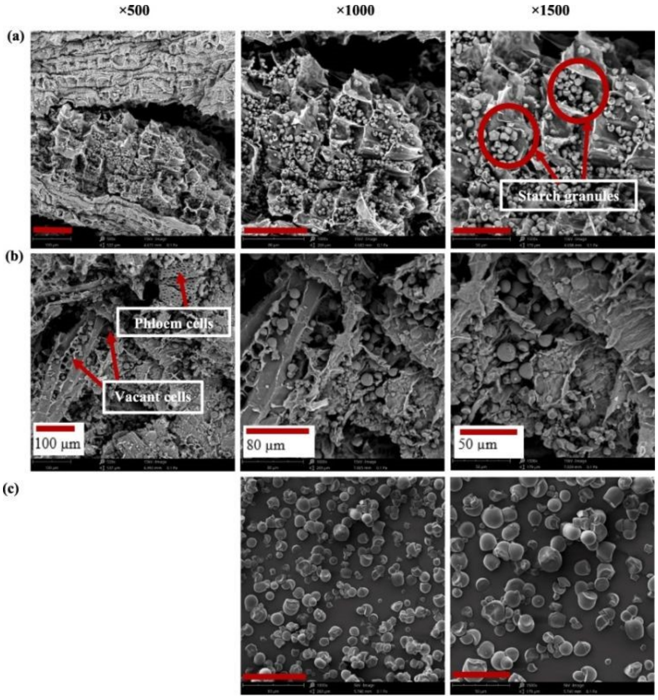


**Fig. 3** Scanning electron microscope micrographs representing the surface morphology of (a) Cassava peel, (b) Cassava bagasse, and (c) Commercial cassava starch. Reproduced from Thuppahige et al., 2023.[44] Copyright Elsevier 2023.

## Extraction of polysaccharides from cassava based wastes

### Extraction of cellulose from cassava-based wastes

Researchers and scientists have employed various extraction methods to obtain cellulose from agro-waste materials.[45] In agricultural residue, cellulose fibres consist mainly of cellulose, along with other substances such as hemicellulose, lignin, and pectin. These cellulose fibres can be predominantly isolated from waste materials through chemical extraction process. Chemical extraction is the most commonly used treatment for the extraction of cellulosic materials. The pretreatment is an essential step in the chemical treatment of cellulose extraction, which is typically done to isolate cellulose fibre from natural sources such as wood or agricultural waste. Two classical approaches for the pretreatment of these biomasses are acid and alkali treatment. [46, 47] The acid treatment, also referred to as bleaching process is used to eliminate lignin and other undesired impurities. Commonly used bleaching agents include chlorine dioxide ($ClO_2$), hydrogen peroxide ($H_2O_2$), and sodium hypochlorite (NaOCl). The occurrence of a clean, white fibre indicates the effective removal of lignin and other undesirable elements. Apart from cassava peel, several other agricultural waste materials were also subjected to pretreatment for cellulose extraction. These include orange peel, sugarcane bagasse, bamboo bagasse, rice hulls, apple stem, mulberry bark, etc.

Widiarto et.al. in 2017 conducted a study to extract cellulose from cassava peel by the chemical treatment (an alkaline pretreatment method followed by a subsequent bleaching process). The treatment was done for 4.5 h at 90 °C. This method provided a yield of 17.8% cellulose content based on the dry weight of cassava peel. In comparison, nitric and sulfuric acid pretreatment methods resulted in lower cellulose yields of about 10.78% and 10.32%, respectively.[48] In 2019 Widiarto et.al conducted another research for the extraction of cellulose from cassava peel, where, the yield of cellulose obtained from the experiment was 17.80%.[36] A study conducted by Travalini et al. in 2018, on cassava bagasse, where chemical treatment was applied for the cellulose extraction. Initially, a bleaching treatment was applied for 5 h, followed by an alkali treatment for a duration of 1 h. The analysis revealed that the cellulose content in cassava bagasse was found to be 51.5%, with a corresponding crystallinity index of 49.3%.[49] Huang et al. (2020) investigated a method for processing cassava peel, starting with amylase pretreatment followed by cellulose bleaching. The process involved enzymatic hydrolysis for 3 h, followed by bleaching treatment at 70 °C for 2 h.[50] In a study, Abiaziem et al. (2019) investigated the chemical treatment of cassava peel through alkali treatment, followed by bleaching treatment to extract cellulose. The resulting yield obtained from these processes was 6.42%, with a measured crystallinity index of 91.72%.[51] Based on the above literature, the chemical extraction process of cellulose from cassava peel have been explained in the flowchart presented in **Fig. 4**



 

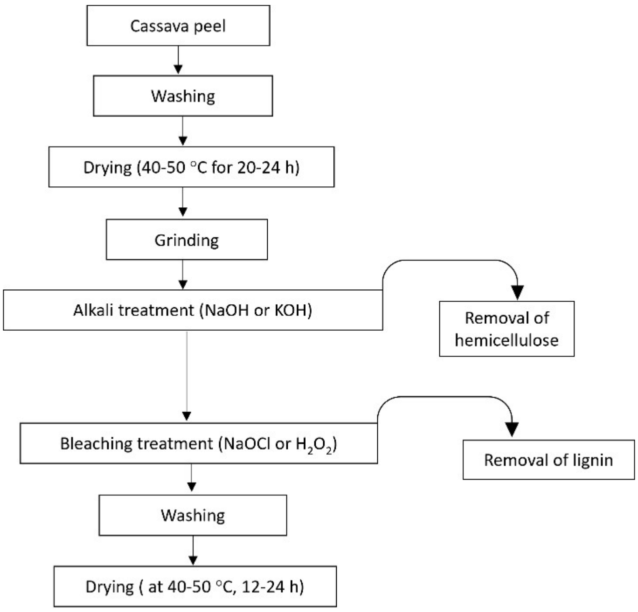


**Fig. 4** Extraction of cellulose from cassava peel using chemical treatment

**Extraction of nanocellulose from cassava peel**

The fabrication of nanocellulose started from many years ago. Nanocellulose exhibits some of the important properties such as good thermal and mechanical properties, barrier properties and optical properties. These behaviour of nanocellulose makes it well-suited for food packaging applications. [52] There are various methods for the extraction of nanocellulose and among these the acid hydrolysis technique is widely used. This approach is suitable and yields nanocellulose rapidly with improved properties. It removes the disordered and irregular segment of cellulose and arranged it in an ordered form. The process involves several stages, including hydrolysis of cellulose using concentrated acid under controlled conditions. Then addition of ice-cold water to stop the reaction. Further centrifugation, dialysis and ultrasonication need to be done to get the final product.[36] There are several studies that have been conducted to investigate nanocellulose production from cassava peels and bagasse. In 2017, Leite et al conducted research for the extraction of nanocellulose from cassava peel. A solution of sulfuric acid was employed for the acid hydrolysis process, where temperature was maintained at 60 °C for a period of 90 min. Following that, the mixture was then cooled to 40 °C and distilled water was used to dilute the suspension. The suspension was neutralized by using potassium hydroxide (KOH). After neutralization, the solution was subjected to centrifugation and homogenization to produce the nanocellulose. [53] Another study conducted by Widiarto et al to extract the cassava peel based nanocellulose using acid hydrolysis. Cellulose extracted from cassava peel was hydrolysed for 2 h using sulfuric acid (45% (w/w)). After that ice cooled, distilled water was used to terminate the reaction. The resulting suspension was then subjected to centrifugation at 14,000 rpm. Dialysis was carried out over 5 days to neutralize and remove the salt present in the suspension. Finally, the suspension was sonicated and freeze dried for overnight to form the nanocellulose. The Transmission electron microscopy (TEM) analysis confirms the particle size of nanocellulose which was below 150 nm.[48] Research conducted by Huang et al in 2018, where, nanocellulose was extracted from cassava residue by chemo mechanical method. Here, phosphoric acid was used for the acid hydrolysis treatment. The combined mixture of cellulose and phosphoric acid was transferred into a high-speed disperser machine operating at 800 rpm, where it was stirred 27 °C for 2 h. After that ice cubes were used to terminate the reaction. The resulting suspension was then subjected to centrifugation and washed with ethanol until it reaches to neutral pH. At last, the suspension was sonicated for 90 min at 40 W, 50 °C and a frequency of 20 kHz and then kept for drying. The SEM image shows a fibrous structure at nanoscale range. [54]

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**Extraction process of starch and derivatives from cassava peel**

One of the most widely used and inexpensive agricultural products that is completely biodegradable in many situations is starch. Starch primarily originates from tubers such as potatoes and cassava and grains such as wheat, corn, and rice. It is the main source of energy for the plant and is found in the seeds or roots. Starch is also a polymer, which is an important aspect of its many applications in many industries. Cassava starch can be plasticized, strengthened with fibres, or combined with other polymers to improve its characteristics. It is also now employed as a raw material for the production of bioethanol and renewable energy. Starch can be extracted from cassava peel in a planned and purposeful manner. Till now, many researches have been done for the extraction of starch from cassava peel.

In 2023, Fronza and his co-researchers conducted research to extract the starch by polarimetric method. The method primarily comprises two steps: First step involves hydrochloric acid treatment followed by clarification and filtration. Afterwards, the sample was treated with 40% ethanol and then again acidified with hydrochloric acid. The optical rotation of the solution was measured with a polarimeter. The result showed that, around 6.5% of starch was obtained from cassava peel through extraction. The starch obtained from cassava peels exhibits a high thermal stability and showing the degradation at 300 °C.[55] From another study the yield of the cassava starch was found to be around 30.17% on dry basis, [56] where, hot water extraction method was followed to extract starch from cassava peel and cassava bagasse as represented in **Fig. 5**. In this method, cassava peel/bagasse was mixed with sodium acetate buffer solution, and the mixer/suspension was heated at 120 °C followed by cooling. Afterwards, the cooled solution was sonicated and filtered followed by washing and freeze drying to obtain the final starch powders. Further, a study conducted by Abel et al in 2021 to extract the starch from cassava peel by blending method. In the initial step peels were soaked in water and continuously stirred for 45

DOI: 10.1039/D5FB00490J



min. After this treatment, it was kept for drying at 70 °C and starch was obtained as a final product. [57] Dasumiati et al extracted the starch with the help of grinding method. Proper mixing of the cassava peel has been done for the extraction process. Around 15% of amylose and 73% amylopectin was obtained from the cassava starch. [58] A study conducted by Maharsih et al for the extraction of starch using various treatment. The extraction was carried out using blending, filtration, and settling approaches. Drying was carried out at 50 °C for 6 h to get the final product. From the Fourier-transform infrared spectroscopy (FTIR) analysis, the presence of -OH, C-C and C-H group indicates the presence of starch.[59] During a study carried out in 2016, Siagian et al. discussed the utilization of cassava peel through a series of processes, including blending, filtration, and drying for the production of cassava peel-based starch. [60]

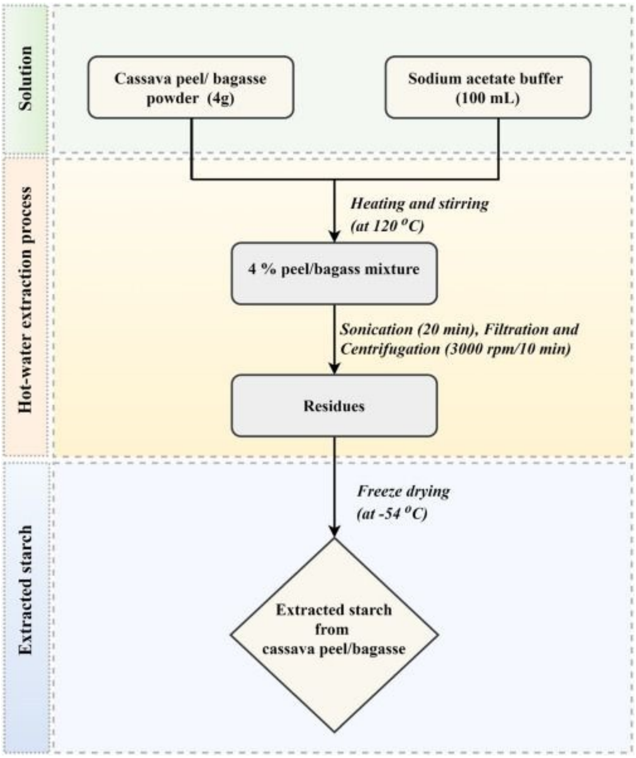


**Fig. 5** Extraction of starch using hot water extraction from cassava peel and cassava bagasse Reproduced from Thuppahige et al., 2023. [56] Copyright Elsevier 2023.

## Properties of cassava peel derived polysaccharides for food packaging

### Cellulose and nanocellulose based films

#### Barrier, mechanical, thermal and others

Cellulose and nanocellulose are two of the most important polysaccharides obtained from cassava peel. In recent years, the materials have gained a lot of attention due to its various properties and applications. Cellulose nanomaterials exhibit excellent thermal, shear resistant as well as water and gas barrier properties. These characteristics makes them suitable for packaging applications. Apart from this, these polysaccharide-based packaging may also enhance the shelf life of food products due to its excellent antimicrobial and antioxidant properties. If we consider about cassava peel-based cellulose and nanocellulose, it also shows a very good barrier and mechanical properties, which makes them suitable for reinforcing materials like composites and films. The barrier properties of the nanocellulose based films is commonly determined using Water vapor transmission rate (WVTR). However, lower the WVTR value is generally desirable, as it indicates excellent resistance to moisture. Addition of cassava peel-based nanocellulose into a film matrix effectively reduced the WVTR value because of the complex path arising from the ordered crystalline part of nanocellulose. In addition to barrier properties, incorporation of nanocellulose also decreases the water and oil absorption properties of the composite films. This is due to the minimization of pores and voids present in the composite materials. Furthermore, nanocellulose facilitate an interfacial bonding between the polymer matrix and thus improve the mechanical properties. Apart from this, cellulose nanomaterial is thermally stable also. The decomposition temperature is typically exceeding to 200°C and this makes them suitable for high-temperature applications. In 2020, Huang et al conducted research aiming to investigate the barrier and mechanical characteristics of nanocomposite films derived from cassava starch. The research findings indicate that, incorporation of cellulose nanofibers (CNF) leads to increase the tensile strength of the film and it reaches to the peak value at 3-4% CNF concentration. Moreover, compared to the pure cassava starch-based film, the CNF-based film showed a decrease in water vapor permeability due to the formation of hydrogen bond between cassava starch and CNF. Apart from these, CNF/ thermoplastic cassava starch (TPS) based film shows more hydrophobic nature because of the hydroxyl group present in the surface as compared to the pure cassava starch film.[50] Another study conducted by Abdullah et al on microcrystalline cellulose (MCC)/Cassava starch-based bioplastic. From the study it has been seen that incorporating MCC enhances the water contact angle of the bioplastic sheet and as a result increases the hydrophobicity of the sheet. Moreover, increasing the MCC content was associated with improvement in the mechanical properties, including young's modulus and tensile strength of the sheet. The enhancement in tensile strength was due to the adhesion occurring at the interface of MCC and starch. Moreover, there is a decrease in the elongation because of the volume fraction and dispersion pattern of the reinforcing agent within the matrix. Apart from this, the Thermogravimetric analysis (TGA) reveals that incorporating MCC into bioplastics results in improving the heat resistance capacity of the sheet.[61] Further, Huang et al in 2018 conducted research on the mechanical properties of Poly(lactic acid) PLA/ cassava residue based nanocellulose. The study showed that, addition of nanocellulose (NC) from 0.5% to 1% range improves the tensile strength of PLA based nanocomposite film as compared to the neat one. Further, increase in the concentration of nanocellulose decreases the tensile strength

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due to agglomeration of nanocellulose. At 1% NC concentration, elastic modulus of the composite film was found to be highest due to the development of network structure between the nanocellulose and PLA. As a result, the inter molecular force between the molecule increases and making the film more resistant to deformation.[54] In 2025, Afzia, Bora & Ghosh reported the development of a cling wrapper formulated using pectin, pullulan, olive oil and cassava peel based CNF for chicken meat packaging. The developed films enhanced the quality attributes of chicken meat.[62] In a study, Saravanan et al. (2023) investigated the incorporation of cassava tuber peel-based nanocellulose, polyester resin, and satin-weaved bamboo fibre into composite films. They found that the load-bearing capacity of the composite film increased up to 4 vol.% of cellulose due to the strong interaction of cellulose with the polyester resin. Additionally, the thermal stability of the film was enhanced, with the decomposition temperature increasing at 4 vol.% of cassava nanocellulose compared to pure polyester film.[63] Additionally, in a study by Wang et al. (2018), it was observed that the addition of cassava peel-based cellulose nanomaterials (CNMs) to polymer composites can significantly enhance their oxygen barrier properties. However, the researchers also noted that CNMs exhibits sensitivity towards moisture. Therefore, it is important to select the polymeric material carefully in order to reduce the sensitivity of CNMs and improve their overall performance.[64]

## Starch based films

### Barrier, mechanical, thermal and others

Starch is one of the major component obtained from agro-waste based sources. It is one of the promising candidate in the field of food applications. It is widely used as a thickener, stabilizer, binder and gelling agent in various food items. Beyond the traditional uses, it is also a important sustainable source for the production of biocomposite films. Such films possess excellent barrier, mechanical, optical and antibacterial properties, thus suitable for packaging large number of food items like bread, fruits and vegetables, meat products etc. . In particular, cassava starch serves as an excellent source for the advancement of nanoparticles. Film prepared from starch are considered as biodegradable, renewable and non-toxic.[65] Costa et al in 2017 conducted research to see the impact of nanocrystalline starch on cassava starch-based film. The study highlighted that addition of nanocrystals enhances the tensile property and reduces the water vapor permeability (WVP) of the film.[66] Additionally, Souza et al. (2012) conducted a study to investigate the change in barrier and mechanical properties of composite films based on cassava starch with the addition of starch nanomaterials and glycerol. The presence of glycerol significantly effects the tensile strength of the film. There was also an enhancement in the barrier property of the film. Moreover, combined effect of glycerol and nanoparticles remarkably enhanced the tensile strength and barrier property.[65] Another study conducted by Pelissari et al to see the barrier, mechanical and antimicrobial properties of Cassava starch/Chitosan/Oregano essential oil (OEO)-based film. The study revealed that cassava starch-based film shows the maximum WVP value. However, when chitosan was mixed with cassava starch, it shows a reduction in WVP. This is mainly due to the hydrogen bond formed between the hydroxyl ($OH^-$) group of cassava starch and amine ($NH_2$) group of chitosan. Addition of OEO also decreases the WVP of the film. Moreover, there is no significant change in the film with the incorporation of chitosan and OEO.[67] Additionally, Tongdeesoontorn et al conducted research on the physical properties of cassava starch/ Carboxymethyl cellulose (CMC) based biodegradable film. The properties of the film were found to be improved with the addition of CMC and glycerol. There is an increase in water solubility and tensile strength of the film and a decrease in elongation with the addition of CMC. Moreover, differential scanning calorimetry (DSC) analysis provides the uniformity of the film.[68] Research conducted by Jumaidin et al to see the change in thermal, biodegradable and mechanical properties of thermoplastic cassava starch (TPCS) based film with the addition of durian peel fibre (DPF). The study revealed that there is a change in mechanical and thermal stability of the film when different concentration of DPF was incorporated into the film. Furthermore, FTIR spectroscopy and SEM shows the excellent interactions between DPF and TPCS matrix.[69] Luchese et al has conducted another research on cassava starch/Blueberry pomace composite film. The research was mainly focused to see the effect of blueberry pomace on cassava starc h film. From the DSC analysis, it has been observed that addition of blueberry pomace significantly improved the thermal stability of the film as compared to the film without blueberry pomace. This may be due to the interaction between the blueberry pomace and cassava starch. Addition of blueberry pomace may also increase the UV light protection capacity of the film. Apart from this, the swelling behaviour was also found to be increased.[70] Some of the barrier, mechanical and thermal properties of cellulose and nanocellulose derived from cassava peel has been represented in the **Table 2**.

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**Table 2. Barrier, mechanical and thermal properties of cellulose and nanocellulose derived from cassava peel for packaging applications.**

| Sl no | Sources | Property | References |
|---|---|---|---|
| 1. | •Thermoplastic cassava starch (TCS)<br>•Glycerol<br>•Cassava peel based-CNF | •Tensile strength of the film reaches to the peak value at 3-4% CNF concentration.<br>•Water vapor permeability of the CNF based film decreases as compared to pure cassava starch-based film.<br>•CNF/ TCS based film shows more hydrophobic nature. | [50] |
| 2. | •Cassava starch<br>•Glycerol<br>•Microcrystalline cellulose (MCC) | •Hydrophobicity of the bioplastic sheet increases.<br>•Reduces the moisture uptake of the bioplastic sheet.<br>•Young's modulus and tensile strength of the sheet increases with increase in the MCC.<br>•Elongation decreases with increase in the concentration of MCC. | [61] |
| 3. | •PLA<br>•Cassava peel based nanocellulose<br>•Dichloromethane<br>•Acetyl tributyl citrate<br>•BHT | •Addition of NC from 0.5% to 1% range increases the tensile strength of PLA based nanocomposite film. Further increase in nanocellulose concentration decreases the tensile strength.<br>•At 1% NC concentration, elastic modulus of the composite film was found to be highest. | [62] |
| 4. | •Cassava tuber peel based nanocellulose<br>•Polyester resin<br>•Satin weaved bamboo fibre | •Load bearing capacity of the composite film increases up to 4 vol.% of cellulose due to the strong interaction of cellulose with the polyester resin.<br>•Thermal stability of the film was found to be increased. At 4 vol.% of cassava nanocellulose, decomposition temperature increases as compared to pure polyester film. | [63] |
| 5. | •Cassava peel based cellulose nanomaterials<br>•Polymer | •Addition of CNMs to polymer composites can enhance their oxygen barrier properties.<br>•CNMs have been found to be sensitive to moisture, they may require additional design considerations, such as multilayered structures and the choice of surrounding polymers, to address their moisture sensitivity and improve their overall performance. | [64] |
| 6. | •Cassava peel based starch<br>•Glycerol<br>•Starch nanoparticles | •Thickness of the film increases.<br>•Water vapor permeability of the film decreases.<br>•No significant change in the tensile strength of the film as compared to control. | [65] |
| 7. | •Chitosan<br>•Cassava starch<br>•Oregano essential oil | •Barrier properties of the film improved<br>•Antioxidant property of the film increases.<br>•Increase in the flexibility of the film.<br>•Reduction in the WVP of the film.<br>•No significant change in the thermal stability. | [67] |



 

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| Sl no | Sources | Property | References |
|---|---|---|---|
| 8. | • Cassava peel starch<br>•CMC<br>•Glycerol | •Decrease in the water solubility of the film with the addition of CMC.<br>•CMC incorporated film becomes more homogenous.<br>•Increase in the tensile strength of the film.<br>•Decrease in the elongation. | [68] |
| 9. | •Durian peel fibre (DPF)<br>•Thermoplastic cassava starch (TPCS) | •Improvement in the thermal stability of the film.<br>•Increase in the rate of biodegradability of the film.<br>•Flexural and tensile strength of the film improved.<br>•FTIR spectroscopy and SEM shows the excellent interactions between the two compounds. | [69] |
| 10. | • Cassava starch<br>•Blueberry pomace<br>•Sorbitol | • Enhanced in the barrier properties of the film.<br>•Improvement in the thermal stability of the film.<br>•High UV light barrier property of the composite film.<br>•Swelling capacity of the film slightly increases with the addition of blueberry pomace. | [70] |

**(Note: TCS:** Thermoplastic cassava starch; **CNF:** Cellulose nanofibers; **MCC:** Microcrystalline cellulose; **PLA:** Poly (lactic acid); **NC:** Nanocellulose; **BHT:** Butylated hydroxytoluene; **CNMs:** Cellulose nanomaterials; **WVP:** Water vapor permeability ; **CMC:** Carboxymethyl cellulose; **DPF:** Durian peel fibre; **TPCS:** Thermoplastic cassava starch; **FTIR:** Fourier-transform infrared spectroscopy; **SEM:** Scanning electron microscopy; **UV:** Ultra violet)

## Cassava and cassava peel derived polysaccharides for food packaging application

Cellulose is considered as one of the most remarkable and versatile natural substance that has gained increasing attention for its eco-friendly and biodegradable properties. It is the most abundant organic polymer on Earth. Cellulose is anticipated to be non-toxic and safe for food contact applications. Moreover cellulose-based materials can have an impressive strength-to-weight ratio, which makes them suitable for various packaging applications. They can provide the necessary strength and durability while keeping packaging lightweight, reducing shipping costs and energy consumption.[71] Furthermore, the structure of cellulose imparts the characteristics necessary for bioengineering uses, including biocompatibility, biodegradability, and suitable mechanical attributes.[72] Besides all the properties listed above, it has a limited range of applications. One potential solution for this issue involves utilizing nanomaterials as a filler in the production of composite materials.[73]

Cellulose nanoparticles indeed offer a promising approach for the development of sustainable packaging materials with enhanced properties. When cellulose is reduced in size from micro to nanoscale, several changes may take place, which can significantly impact the utility of these nanoparticles in the field of sustainable packaging.[74] The development of cassava peel-based cellulose and nanocellulose for packaging is still a growing field, and research is ongoing to optimize extraction processes and improve the performance of these materials. However, they hold great promise in addressing the environmental concerns associated with conventional packaging materials. The cellulose derived from cassava peel can be used to create films and coatings for various packaging applications. These materials can be used for food packaging, as well as non-food items such as electronics and textiles. The biodegradable bags made from cassava peel-based cellulose can reduce plastic pollution and have a lower environmental impact. Moreover, combining cassava peel-based nanocellulose with other biodegradable polymers can result in stronger, more sustainable packaging materials. This type of packaging can help extend the shelf life of food products by providing effective barrier properties and protection against environmental factors.

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Cassava based starch in sustainable packaging is an innovative and eco- friendly approach that can replace the plastic waste and promote environmentally friendly practices in the packaging industry. It offers the advantages of biodegradability, renewability, and customization, making it a promising option for reducing the environmental impact of packaging materials. To address the global concern about plastic bags, cassava biopolymers have been introduced into the market. These bags are crafted from starch derived from cassava plants, making them biodegradable and eco-friendly. Moreover, these bags decompose faster than petroleum-based plastic bags, making them an eco-conscious choice.[75] In this context, the visual appearance of films based on neat cassava starch, cassava starch with lignocellulosic nanofibers (LCNF) and nanoclay (Nclay) has been represented in **Fig. 6,** where, the films have possible food packaging applications due to tensile and barrier properties.[76] The films based on cassava starch reinforced with LCNF has better properties in comparison to biocomposites of cassava starch and Nclay. A study conducted by Kaisangsri et al., focused on the development of foam trays from cassava starch blended with chitosan and kraft fibre. The study found that, development of foam trays has the potential to replace traditional polystyrene foam with a more environmentally friendly and sustainable alternative. Moreover, cassava starch-based foam displayed improved properties compared to polystyrene foam in terms of density, tensile strength, and elongation.[77] Wahyuningtiyas and Suryanto conducted a study to examine the impact of incorporating nanoclay into cassava starch along with glycerol as a plasticizer to produce bioplastic. The research indicated that the addition of nanoclay significantly enhanced the properties of cassava starch-based bioplastics. Enhancement in tensile strength, elongation, and water absorption, along with the material's biodegradability, makes it a promising option for environmentally friendly packaging and other applications where traditional plastics are commonly used. This research contributes to the development of sustainable materials with reduced environmental impact.[78] Furthermore, some of the other applications of cassava-based starch has been represented in **Table 3.** In this regards, cassava and cassava peel-based biopolymers have received considerable attention in developing films for packaging applications.

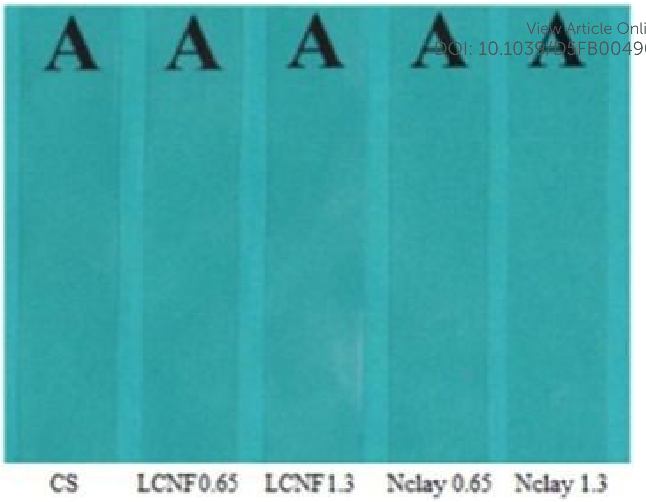


**Fig.6** Visual appearance of films based on cassava starch (CS), CS with lignocellulosic nanofibers (LCNF) and nanoclay (Nclay). Reproduced from Travalini et al., 2019.[76] Copyright Elsevier 2019.



 

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**Table 3. Application of Cassava starch in sustainable packaging.**

| Sl no | Materials | Methods of application | Food packaging/ coating applications | Effect on the shelf life of food products | References |
|---|---|---|---|---|---|
| 1. | Cassava starch<br>Sucrose<br>Invert sugar<br>Glycerol | Solvent casting | Film is used for packing toast. | ——— | [65] |
| 2. | Cassava starch<br>Glycerol<br>Glutaraldehyde<br>Polyethylene glycol | Solvent casting | Used as an edible film | ——— | [79] |
| 3. | Cassava starch<br>Grape stalks<br>Guar gum<br>Magnesium stearate<br>Glycerol | Hydraulic pressing | The foam is applied for storing English cake. | ——— | [80] |
| 4. | Cassava starch<br>Zinc nanoparticles<br>Glycerol | Solvent casting | The nanocomposite is used for the packaging of tomatoes. | • Films with 1-2% zinc nanoparticles supressed the microbial growth and better retained the tomato quality than LDPE at 27 °C on day 9. | [81] |
| 5. | Cassava starch<br>Chitosan<br>Sorbitol<br>Citric acid<br>Gelatin | Solvent casting | Used in coating of fruits. | ——— | [82] |
| 6. | Cassava starch<br>Citric acid<br>Glycerol | Dipping | Used for coating mango slices. | • The respiration rate of coated mange slices were reduced by 41% as compared to control.<br>• Texture and color characteristics of the coated mango slices was also found to be maintained during storage.<br>• Coated mange slices were well accepted by consumers.<br>• Coating significantly extend the shelf life of the fresh cut mangoes. | [83] |

## Food based application of cassava peel

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| Sl no | Materials | Methods of application | Food packaging/ coating applications | Effect on the shelf life of food products | References |
|---|---|---|---|---|---|
| 7. | Cassava starch<br>Glycerol<br>Kaempferia rotunda Essential oil of *Curcuma xanthorrhiza* | Dipping | Used for coating patin (fish) fillets. | • Edible coating prepared with cassava starch, Kaempferia rotunda and essential oil of *Curcuma xanthorrhiza* extended the shelf life of patin (fish)fillet. | [84] |
| 8. | Cassava starch<br>Sodium-CMC<br>LAB | Solvent casting | Used in the packaging of banana. | • Banana wrapped with the composite film delayed browning and development of black spots as compared to the unwrapped banana. Thus enhanced the freshness and shelf life. | [85] |
| 9. | Cassava peel starch<br>Sorbitol<br>MCC | Solvent casting | Used for the preparation of bioplastic | ________________ | [57] |
| 10. | Cassava peel based starch<br>Glycerol<br>Kaffir lime essential oil<br>Citric acid | Solvent casting | Used for the production of bioplastic. | | [86] |
| 11. | Gelatin powder<br>AgNPs from cassava peel<br>Glycerol | Solvent casting | The film produced is used for the preservation of sapodilla fruits. | • Coated sapodilla fruits exhibited reduced weight loss and microbial growth, thus enhancing the quality and shelf life of sapodilla fruits. | [87] |
| 12. | Cassava starch<br>Fructose<br>Cassava bagasse<br>Cassava peel | Solvent casting | Used for the preparation of film. | ________________ | [9] |

**Note: CMC: Carboxymethyl cellulose; LAB: Lactic acid bacteria; MCC: Microcrystalline cellulose; AgNPs: Silver nanoparticles**

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The valorization of agro-industrial residues has become increasingly important as the demand for energy and value-added bioproducts continues to rise. Among these residues, cassava processing generates large amounts of peels that are often overlooked despite their promising potential in food and feed applications. Cassava peels are rich in xylan, making them an excellent source for producing xylo-oligosaccharides (XOS), prebiotics known for their beneficial effects on gut health.[88] Beyond prebiotic extraction, the peels can be transformed into light, crispy snacks that are not only palatable but also carry market value. In addition to human consumption, cassava peels retain considerable amounts of carbohydrates and dietary fiber, enabling their inclusion in animal diets as an effective energy source.[89] For instance, studies on *Clarias gariepinus* (African catfish) have demonstrated the potential of cassava peel as a feed component without compromising growth.[90] Similarly, in poultry nutrition, broiler chickens fed diets where maize was partially replaced with up to 25% raw or processed cassava peel meal showed not only good performance but also enhanced carcass characteristics.[91]

## Life cycle assessment of cassava and its byproducts

Cassava and its by-products, including peels, stems, straw, bagasse, leaves, and wastewater, have diverse applications worldwide, such as starch production, animal feed, medicinal and ornamental uses, soil regeneration, and bioethanol, biofertilizer, bioplastic, and biofuel production within a biorefinery framework. These valorization pathways not only reduce competition with food security but also generate employment for unskilled labor. To ensure their sustainability, it is essential to apply novel analytical tools such as Life Cycle Assessment (LCA), which enables stakeholders to evaluate socioeconomic and environmental impacts and make informed decisions for biorefinery projects.[92]

In this context, the integration of cassava waste into a waste-water-energy-food (WWEF) nexus system has been proposed for small-scale cassava industries in Brazil. This system combines anaerobic digestion (AD) with co-generation or combined heat and power (CHP) plants to convert organic waste into biogas, a promising renewable energy source. Using LCA, three scenarios were compared: business-as-usual, improved business-as-usual, and WWEF closed-loop. The functional unit was defined as the production of 1 kg of cassava starch/flour, with selected impact categories including global warming potential (GWP), cumulative energy demand (CED), freshwater eutrophication potential (FEP), terrestrial acidification potential (TAP), and water depletion potential (WDP).

Results indicated that landfilling cassava waste, high power consumption during starch/flour production, and fertilizer-related emissions are major environmental hotspots under the business-as-usual case. In contrast, the WWEF closed-loop scenario demonstrated the most favorable outcomes, achieving over 90% reduction in GWP and more than 50% savings in other impact categories (except FEP, with <10% savings). Sensitivity analysis confirmed the robustness of these findings.[93] Overall, the study highlights that efficient utilization of cassava by-products through an integrated WWEF closed-loop system not only minimizes biological waste disposal but also reduces dependency on fossil-based resources, enhances resource circularity, and strengthens the sustainability of rural cassava value chains.

## Conclusion and future prospects

Several innovative research solutions are being applied to cassava waste biomass which can provide the advancement for developing a green environment, sustainability, renewability, and efficiency. This could also enhance the supply of biomaterials for industry and promote the adoption of a circular model for production, consumption, and disposal. Sustainable and renewable resources carry significant prospects for the well-being of upcoming generations. Thus, biodegradable and sustainable materials hold great potential for future generations. The severe environmental issues created by the plastic materials can be significantly reduced by the widespread use of polysaccharides as a reinforcing agent during the preparation of composite film. The advancement of these sustainable composites will have a positive impact on the environment, reduce the need for recycling plastic waste and lower the carbon footprint associated with petroleum-derived materials. As potential alternatives to non-biodegradable plastic products, an increasing demand for natural resources are being utilized to promote the environmental sustainability. Moreover, the abundant and cost-effectiveness of these materials have received a lot of attention in recent years.

The demand for these agricultural industrial wastes rises dramatically due to its ability to meet higher environmental, economic and social standards. Moreover, it has gained popularity because of its biodegradability, low manufacturing cost, renewability, low energy consumption, low density as well as abundance in nature. In the food industry cassava peel has been used for various purposes. It can be processed into cassava flour, which can be used as a gluten-free flour alternative in baking and cooking. It can also be used to make snack products like cassava chips or crisps. For biofuel production, such as biogas or bioethanol it is used as a feedstock. Additionally, cassava polysaccharides exhibit excellent tensile strength and impressive flexural strength, as confirmed by numerous mechanical tests and research, making them suitable for a wide range of applications such as packaging, light weight constructions and industrial applications. Cassava peel shows great promise as a reinforcement for sustainable polymer composites. The utilization of cassava peel-based polysaccharides in sustainable packaging helps to reduce the harmful effects of synthetic polymers and decrease the dependence on petroleum-based products. This will not only enhance the socio-economic benefits of rural communities by increasing tax revenues and creating jobs but also provides a significant opportunity in a variety of potential industrial applications. Further in terms of research, more advanced technologies need to be required for the advancement of this type of packaging system. This represents a novel area of research as well as innovation which addresses some specific challenges for the future industrial utilization of cassava peel-based polysaccharides and their applications in packaging industry.

## Acknowledgements

This research was supported by Start-up Research Grant (SRG) through Science and Engineering Research Board (SERB)-DST, New Delhi, India (SERB File no: SRG/2022/001406).

## Author contributions

Nurin Afzia**:** Original draft writing, review and editing.

Tabli Ghosh: Conceptualization, supervision, validation, final review and editing.

## Data availability

No datasets were generated or analysed during the study.

## Decelerations

## Ethical approval

Compliance with ethical approval.

## Funding

The authors were supported by Start-up Research Grant (SRG) through Science and Engineering Research Board (SERB)-DST, New Delhi, India (SERB File no: SRG/2022/001406).

## Declaration of competing interest

The authors declare no conflict of interest.

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## Data availability

No datasets were generated or analysed during the study.