Gamay *et al.*
Food Production, Processing and Nutrition (2024) 6:27
https://doi.org/10.1186/s43014-023-00206-4

Food Production, Processing and Nutrition

REVIEW

Durian (*Durio zibenthinus*) waste: a promising resource for food and diverse applications—a comprehensive review

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Abstract

This review article focuses on exploring the benefits, potentialities, and values of durian waste for food and other applications. In the domain of food applications, durian waste exhibits immense promise as a source of valuable compounds, including pectin, phenolic antioxidants, husk, and seed flour. Moreover, it serves as a viable material for the development of edible and bio-composite films, contributing to sustainable food packaging solutions. Beyond its relevance in the food industry, durian waste holds significance in non-food applications, particularly in the extraction and utilization of unique biomaterials, such as nanocellulose particles. These nanocellulose-based materials have garnered attention for their diverse applications including in the food industry. The various utilization methods and techniques were also discussed. The waste of durian contains nutritional values that provide great potential for valorization. In this review, it has been proved that durian waste should not be thrown away because it possesses great potential in terms of value-added products.

Highlights

- The unique composition of durian waste can provide many future products in the agricultural sector, especially in food and non-food industries.
- Durian wastes established a valuable product that has a more significant impact on food and non-food applications.
- Valorization of durian wastes.
- Durian waste provides nutritional contents that have a high potential for valorization.

Keywords Agricultural wastes, Durian wastes, Utilization, Value-adding, Sustainability, Valorization, Food applications

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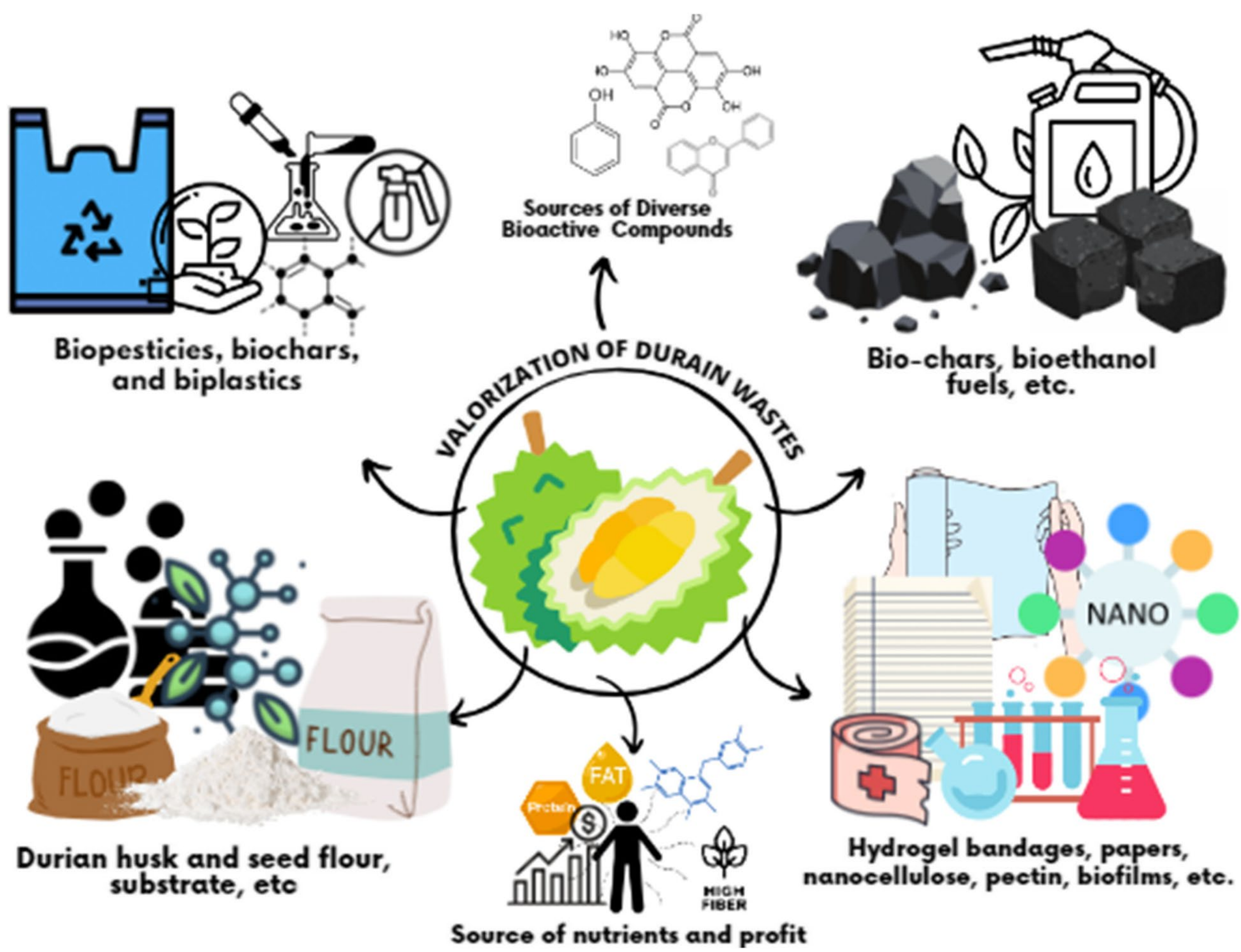
Graphical Abstract



Introduction

Durio zibenthinus, commonly known as Durian, is a tropical fruit recognized as the "King of Fruits" (Lubis et al. 2018). It is native to the Malay Peninsula (Zhang et al. 2021) and widely cultivated in Southeast Asia, particularly in Malaysia, Thailand, Indonesia, and the Philippines (Koay et al. 2019). The Philippines has exclusive durian tree cultivation in areas such as Davao, Cotabato, Sulu, and Agusan (Chung, 2011) (Fig. 1a). The durian tree blooms from April to June, and the fruit is harvested from August to November, making it an excellent export prospect for the Philippines, as the harvest season is later than in other Southeast Asian countries. Durian fruit (Fig. 1b) is recognized by its large size, intense taste, pungent odor, and stiff thorn-covered husk, which takes 95 to 130 days to grow (Sawitri et al. 2019). It develops from the underside of the branches on a strong peduncle with an abscission zone immediately above the fruit. The durian fruit can weigh up to 3 kg. The fleshy aril (pulp) (Fig. 1c) is the edible portion of the fruit and it has a firm custard-like texture. The external composition of the fruit, the husk, is distinguished by its broadly pyramidal cover, coarse, hard, sharp, and ranges in color from olive-green to yellow (Ketsa et al. 2020).

Globally, Thailand and Malaysia are the two largest durian fruit producers, accounting for up to 90% of global production. China and Singapore are also considered durian exporters in other regions. In 2021, Malaysia produced 448,000 metric tons (MT) of durian fruit, while in 2022 the volume of durian production in Thailand reached up to 2,435,390 MT (Statista 2022a, b). According to Statista (2023), durian production in the Philippines experienced fluctuations over the observed

Fig. 1 The durian tree (**a**), fruit, and aril (pulp/flesh) (**b**). (Ong et al. 2021)

period. The country produced around 78,820 MT of durian in 2020 and had lower production in 2011, with only 58,970 MT. The highest production was in the year 2013 with 91,210 MT, followed by 2015 with 87,380 MT. Additionally, Mindanao Island has a significant durian production every year, accounting for around 54,700 MT.

According to Nordin et al. (2017), 20–35% of durian fruit is composed of flesh (aril), and 5–15% is composed of seeds, whereas 55–66% is made up of husk, which is frequently regarded as waste material. As a result, the country generates around 22,000 MT of durian waste each year, which often winds up in waste landfills or, worse, is just left along the sides of roadways to decompose (Phoung 2012). When durian husk is discarded into a landfill or burned, it contributes significantly to agricultural waste and creates an environmental problem (Wai et al. 2010). The negative impacts of human activity on the environment, such as pollution, overpopulation, waste disposal, climate change, global warming, and the greenhouse effect, are referred to as environmental challenges. Therefore, it is essential to reduce agricultural waste by reusing and repurposing it. The sensible approach for handling durian waste is to convert it into various valuable products.

For this reason, various researchers have studied the components and significance of durian waste to establish a valuable product that has a more significant impact on food and non-food applications. However, there is no published article that focuses on reviewing the utilization methods of durian waste. Thus, the primary purpose of this review is to explore and discuss the values, benefits, potentialities, and utilization methods of durian waste.

Composition and benefits of durian fruit waste

Durian husk

The locule of durian husk contains different segments (Fig. 2), each with varying composition values (Nordin et al. 2017). The portion with the green and thorny outer husk has the highest dry matter content (30.47%), whereas the thick bottom portion of the white inner husk has the highest percentage of moisture and ash content (81.83% and 6.95%), respectively. Furthermore, the crude fiber content in the entire durian husk was the highest (14.66%). These results suggest that the composition value present in each segment could play a role in commercialization approaches, particularly in food production.

Another study by Lubis et al. (2018), indicated that durian husk is lignocellulosic biomass with a complex structure composed of hemicellulose, cellulose, and lignin with around 30.70%, 57–64%, and 15.60%, respectively. Cellulose is a kind of structural component that can provide strength and stability to the wall cell of fiber and plants. It also has the properties of having high crystallinity and stiffness and not being dissolved in organic solvents. Moreover, the

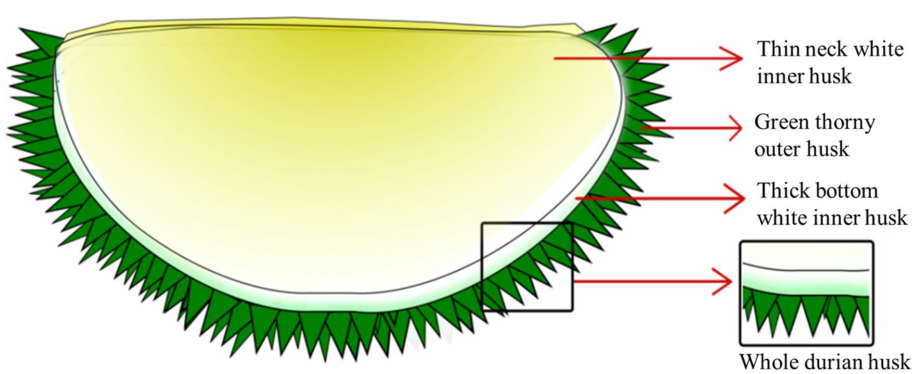


Fig. 2 Locule of durian husk and each segment (Nordin et al. 2017)

hemicellulose content can decrease the strength of the fiber and cause it to easily degrade. While lignin structure can influence properties such as morphology, structure, hydrolysis, and flexibility.

In addition, durian husk has phytochemical compounds, namely alkaloids, saponins, and triterpenoids that have an antibacterial function (Arlofa et al. 2019). These antibacterial properties can be used as an effective film-forming agent in the preparation of film-based wound dressings (Chaemsawang et al. 2020) and antibacterial ingredients for hand sanitizer products (Arlofa et al. 2019). These factors inspired the Nanyang Technological University, Singapore (NTU Singapore) food experts, under the direction of Professor William Chen, Director of NTU's Food Science and Technology Program, to develop an antibacterial gel bandage from the fruit's husks. As a proof of concept, the antimicrobial hydrogel bandages were assessed on animal skin as a wound dressing and demonstrated effective antibacterial properties for up to 48 h.

In a different study, Arlofa et al. (2019) used durian husk extract as a natural antibacterial component in hand sanitizer products. The findings revealed that the concentration of durian husk extracts in hand sanitizer has a substantial impact on the suppression of bacterial growth of E. coli, S. S. aureus, and S. typhosa and shows how the presence of this concentration reduces the quantity of microbial colonies. In addition, durian husk includes activated carbon, which has hazardous adsorbent capabilities and can remove chromium (Alfin et al. 2011), lead ions (Nuithitikul et al. 2015), and toluene (Tham et al. 2011) from aqueous solutions.

Durian seed

Durian seed, as displayed in Fig. 3, has a composition value that is potential in food and non-food applications. The composition of the seeds has two components, starch and mucilage or gums (Baraheng & Karrila 2019). The starch of the seeds can be converted into flour and recent studies showed that durian seed flour can be a substitution for wheat flour. Moreover, durian seed gum has been used as an emulsifier in vegan mayonnaise to replace egg yolk in an experiment (Cornelia et al. 2015).

Amid et al. (2012) discovered that durian seed gum has characteristics that are responsible for the structure of monosaccharide and glycoside bonds. Similarly, Lee et al. (2018) described the nutrients discovered in durian seed, which included glucose, organic acids, and amino acids, in order to detect important aroma volatiles and chemicals. According to Amid and Mirhosseini (2012), the carbohydrate predominant composition of durian seeds is galactose (48.6–59.9%), glucose (37.1–45.1%), arabinose (0.58–3.41%), and xylose (0.3–3.21%), while the abundant amino acids were glutamic acid, leucine, threonine, and alanine, which could stimulate the durian flavors through the development of functional compounds (Ragasa et al. 2016).

As presented in Table 1, the durian husk acquired a higher percentage of moisture and ash compared to the durian seeds. Also, carbon and oxygen are only present in durian husk while fat, protein, crude fiber, dietary fiber, and a high percentage of carbohydrates are only found in durian seeds. This indicates that the durian seeds' high carbohydrate content may be converted into flour, which has a significant economic worth and potential as a raw ingredient for flour-based products (Mulyati et al. 2018).

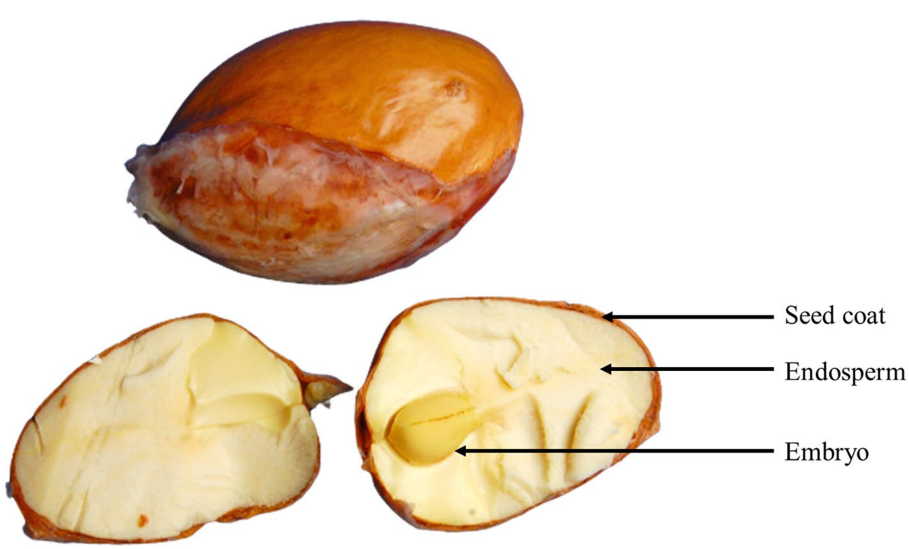


Fig. 3 Durian seed and its component. Modified from Chung (2011)

Table 1 Chemical composition of durian seeds (Siti Farahida et al. 2021) and husk (Jun et. al. 2010)

Chemical composition	Seed (%)	Husk (%)
Moisture	6.6	11.27
Ash	3.8	4.84
Fat	0.4	-
Protein	7.6	-
Crude fiber	4.8	-
Carbohydrate	76.8	-
Dietary fiber	52.9	-
Carbon	-	39.3
Oxygen	-	53.74

Potentialities and applications of durian waste

The waste of durian has numerous potential applications in terms of animal feedstock, bio-medical, and value-added products. The applications for durian waste in both food and nonfood industries are shown in Table 2 below. The table clearly demonstrates that the durian husk has been discovered to have more utilization than the seeds.

Food applications

Pectin

Pectin, due to its versatile gelling and thickening properties, has found extensive utilization in various food applications. The extraction of pectin derived from durian husk involves multiple processes, including heating, filtering, concentrating, and extracting (Ghaffar et al. 2019). Ghaffar et al. (2019) use two methods of extraction, this method was slightly modified from Amaliyah (2014) (first method), and Hokputsa et al. (2004) (second method). According to the findings of their study, the first approach with a pH value of 2.00, a temperature of 85 °C, and an extraction time of 2 h has a higher yield than the second method with a pH value of 4.5, a temperature of 90–100 °C, and an extraction time of 20 min. This demonstrates that an extraction technique with a lower pH value can provide a higher yield as compared to one with a higher pH value. This assertion is in line with the findings of Ardiansyah et al. (2014) where a lower pH value, results in more yield of extracted pectin.

Additionally, in the study of Kulathunga (2017), pectin was obtained via chemical procedures to investigate its structural and functional properties. In the process of extracting pectin, four different chemical agents are used: water and buffers, acids, bases, and calcium-ion chelators. Acids are the most efficient pectin-extracting agents which result in greater yields as it allows for the extraction of insoluble pectin that is tightly bound to the cell matrix of plant material (Assoi et al. 2014). Likewise, the study of Suwannarat et al. (2019) stated that the optimal method to extract pectin was hydrochloric acid extraction because of the degree of esterification (DE %) which determines the gelling properties of pectin, galacturonic acid content, and methoxyl content. Furthermore, when compared to nitric and citric acid, hydrochloric acid exhibited the highest pectin extraction yield (Bhavya & Suraksha 2015), due to its higher ionic strength, high affinity for the cations that stabilize pectin molecules, which boosts its capacity to generate pectin (Mohamed 2016).

The practice of using a microwave is another way to extract pectin. Utilizing microwaves to dielectrically heat plant molecules is known as microwave extraction. Researchers have lately looked into this extraction technique and discovered that it can boost the production and quality of the extracted pectin (Routray & Orsat 2012). Enzymatic pectin extraction, however, is thought to be both environmentally safe and productive in terms of pectin yield. This method of extracting pectin modifies the psychochemical characteristics of pectin by using a different enzyme (Jeong et al. 2014).

In the study of Hasem et al. (2018), pectin was extracted from durian husk through chemical processes using the mild acid aqueous solution as a solvent and hydrochloric for pH adjusting (Wai et al. 2010). According to reports, the husks of durians are a reliable source of pectin with good quantitative characteristics. This might result in more environmentally friendly mass production of polysaccharides and their derivatives from agricultural and industrial waste. In the study of Hui et al. (2021) the researchers compared the yield and characteristics of pectin using the inner part and the whole part of the durian husk. Results showed that the pectin yield from the inner part was significantly higher compared to the whole durian husk. This means that the inclusion of thorns of the durian husk may have decreased the pectin yield as the thorns are rich in cell wall materials such as cellulose, hemicellulose, and lignin (Nordin et al. 2017). Therefore, it may not be necessary to include durian husk thorns prior to the extraction of pectin to maximize the efficiency of pectin extraction.

Phenolic antioxidants

Phenolic acids have often been associated with their function as innate antioxidants in fruits, vegetables, and a range of other plant sources (Zheng & Wang 2001). Phenolic antioxidants play a crucial role in neutralizing harmful molecules called free radicals, which can cause oxidative stress and damage to cells and tissues. It finds application in the food industry primarily as a natural

Table 2 Utilization of durian waste and their potential applications

Main Component	Products	Application	References
Husk	Pectin	Pectin is used as stabilizers, texturizers, emulsifiers, thickeners, gelling agents, water binders, encapsulating agents, and crystallization inhibitors in the food and pharmaceutical industries.	Valdes et al. (2015)
Husk and seeds	Phenolic antioxidants	Phenolic antioxidants find diverse applications across industries, such as food, cosmetics, and pharmaceuticals, due to their potential to enhance product stability, shelf life, and health benefits.	Zeb (2020)
Husk	Flour and cakes	The conversion of durian husk into flour as a wheat flour substitute in butter cake production was investigated to create gluten-free cookies. The durian husk flour was mixed with wheat flour and salted butter in a specific proportion.	Charoenphun and Kwanhian (2019); & Bhoosem and Bunyasawat (2019)
Husk	Biopesticide	Biopesticides are becoming more appealing as a replacement for synthetic pesticides that are harmful to the environment and humans.	Kusumaningtyas and Armiano Syah (2020) &Harahap et al. (2019)
Husk	Biochars	Biochar can be used for a variety of purposes, including soil improvement and fertilization. The literature contains a variety of studies on biochar soil amendment for improving plant growth in the agricultural sector.	Glaser et al. (2019); Kizito et al. (2019); Chew et al. (2020)
Husk	Adsorbent	To improve the water quality, specifically the groundwater source.	Payus et al. (2020)
Husk	Hydrogel Bandages	Application in bio-medical products, which is used to cover surgical sites for the wound healing which has antimicrobial properties.	Khalid (2021) & Cui et al. (2021)
Husk	Bio – composite film	Can be used as food packaging material.	Lee et al. (2018) & Anuar et al. (2018)
Husk	Non-wood-based raw material for pulp and paper industry	Durian husk has great potential as a novel material for the pulp and paper industries.	Masrol et al. (2018)
Husk and seeds	Bio –plate	Potential for use as a packaging raw material—Instead of foam, it can be used as an alternative environmental packaging.	Tengrang et al. (2020)
Husk	Liquid -smoke	It can be used as natural food preservation due to its presence of antibacterial substance, latex coagulant, and biopesticide.	Faisal et al. (2018) & Permanasari et al. (2020)
Seeds	Substrate of *Monascus spp.*	It is possible to produce angkak using durian seed as a novel substrate.	Srianta et al. (2012a, b)
Seeds	Flour	Potential product diversification of wheat flour.	Mulyati et al. (2018)
Husk and Seeds	Bioethanol	Bioethanol production provides great potential to achieve a fuel production that is sustainable and renewable.	Sebayang et al. (2017)
Seeds	Edible film	Durian seed starch edible film is good for packaging which is also environmentally friendly.	Sitti Rahmawati (2021)

additive to enhance the shelf life and stability of food products, mitigate oxidative deterioration, and contribute potential health benefits due to their antioxidant properties (Zeb 2020). Within the spectrum of phenolic antioxidant compounds, flavonoids stand out due to their capacity to function as both efficient scavengers of reactive oxygen species (ROS) and adept chelators of metals, potentially offering a dual layer of protection (van Lith & Ameer 2016). The utilization of synthetic antioxidants has raised concerns about potential health issues (Gülcin 2012); thus, the appeal of natural antioxidants sourced from diverse origins has grown significantly. From the standpoint of durian wastes, Masturi et al. (2020a, b) identified phenolic antioxidants present in the durian husk. The total flavonoid content was determined using the Aluminum Chloride ($AlCl3$) method, where solution extracts (10 mg/mL) or quercetin standard solution (25–200 µg /mL) were mixed with 2% AlCl3 solution and 120 mM potassium acetate. After incubation and absorbance measurement at 425 nm, flavonoid concentration (mg/mL) was calculated using the quercetin calibration curve, expressed as mg QE/g of the sample. The study findings disclosed that the phytochemical assay conducted on three local durian shell samples identified the presence of phenols, steroids, and terpenoids. Furthermore, the outcomes of the phytochemical assay indicated a greater predominance of phenolic groups in contrast to the flavonoid group. In a similar approach, Wang and Li (2011) investigated the antioxidant potential of durian shells in vitro. The results indicated that the total phenol contents (33.77 ± 1.77 mg GAE/g) were present in Methanol Extract in durian shell. Their study revealed that durian shell showcases potent in vitro antioxidant capabilities, potentially contributing to its pharmacological and healthcare applications, attributed to metal-chelation and radical scavenging, possibly via hydrogen atom and electron donation. In another study of Juarah et al. (2021) conducted a study on two types of wild durian species, analyzing the antioxidant activities and content of phenolic and flavonoid compounds in their flesh, seed, and peel extracts using 80% methanol. The non-edible parts (seed and peel) showed elevated phytochemical content and stronger antioxidant properties than the flesh, as determined by DPPH, ABTS, and FRAP assays. These findings hold potential for pharmaceutical applications, health benefits, and market promotion of wild durians while aiding in their preservation. In brief, multiple studies have underscored the potential of durian wastes, including husk and seed, as valuable sources of phenolic antioxidants. The exploration of their applications extends beyond the realm of antioxidant benefits, encompassing their utilization in the realms of food and various industries, thereby contributing to sustainable resource utilization and economic growth.

Durian husk flour

Generally, there are four major unit operations involved in the production of flour from fruit wastes such as sample preparation including cutting, drying, size reduction, and sieving (Alvarado 2023). In the context of durian husk flour, Charoenphun and Kwanhian (2019) prepared durian flour by cutting, drying, and grinding the durian husk to develop flour, as shown in Fig. 4. It was first separated from the flesh and seed of durian. The edible part of the durian husk was chosen and chopped into tiny pieces. Then, it was dried and ground on a fine grinding machine for 2 min. The outcome of the study proves that durian husk flour has the potential to manufacture gluten-free cookies and pasta as an alternative product for consumers who prefer to avoid gluten foods (Charoenphan & Kwanian 2018). The gluten-free cookies are being observed from 7 formulations of cookies by a 3-component. The ingredients by mixture design, including durian flour, wheat flour, and salted butter. Based on the consumer's survey, among the 7 formulations, formula 4 with 10% durian rind flour, 47.5% of wheat flour, and 42.5% of salted butter was selected to produce gluten-free cookies because it was in the overlapping area. The researchers also stated that Formula 4 was easy to mold making it more convenient for the production of cookies. Additionally, after baking and expansion, the texture of the cookies was adjusted. It was yellowish-brown in color. The researchers used a contour plot in order to identify the best formulation for cookies. The hardness of cookies varied directly with the amount of durian husk flour. According to Kusumaningtyas and Armiano Syah (2020), durian husk flour is a possible alternative to wheat flour, which is expensive, imported, and rich in gluten. It is also an option for people who are gluten intolerant.

Durian husk flour has shown promising potential as an alternative ingredient in food production, particularly in baking. However, its use in cookies production may have mixed effects on consumers. On the positive side, using durian husk flour can increase the nutritional value of cookies due to its high fiber and antioxidant content. It can also provide a unique flavor and aroma to the cookies, which can be appealing to some consumers. However, there may be concerns about the safety of consuming durian husk flour since it is not a traditional ingredient and may contain allergens or toxins. Additionally, the

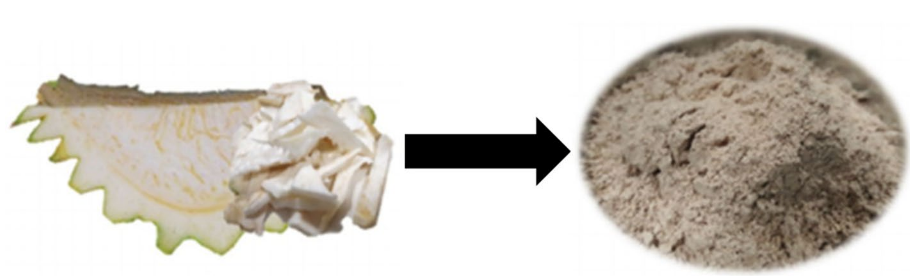


Fig. 4 Durian husk flour (Charoenphan & Kwanian 2018)

texture and appearance of the cookies may be different when durian husk flour is used, which may affect consumer acceptance. In brief, the use of durian husk flour in cookie production requires further research and testing to ensure its safety and acceptability among consumers.

Moreover, the study of Bhoosem and Bunyasawat (2019), investigated the conversion of durian husk into flour as a replacement for wheat flour in the production of butter cakes, and so with Bunyasawas and Phusam (2018) used durian husk powder as a substitute for wheat flour in brownies cake. In the study, the researchers utilized the durian husk by drying and scraping off the green bark and thorns. According to the findings, making brownie cake with 30% durian husk powder in place of wheat flour is acceptable. A healthier alternative for baked products that are high in dietary fiber and low in calories could be brownie cakes made with durian husk powder.

Generally, the results showed that durian husk flour contains 50% of dietary fiber, 34.15% carbohydrate, 6.42% protein, and 0.38% fat (Bunyasawas & Phusam 2018). Therefore, durian husk flour can be used as a food ingredient and a source of dietary fiber.

Durian seed flour

Durian seeds application has increased the potential in food and non-food industries. Durian seed flour, as displayed in Fig. 5, contains starch that consists of amylopectin and amylose (Malini et al. 2016). Mulyati et al. (2018) reported that durian seed flour has a smooth texture, yellowish-white color, and a slightly acidic odor because of the 2-day deposition process that can produce a sour aroma from the separate mucus.

Many studies have revealed the functional, chemical, thermal, and physical properties of durian seed flour. Baraheng and Karrila (2019) compared the functional and chemical properties of durian seed flour composed of demucilaged flour, whole-seed flour, and seed starch. Based on the results, the chemical properties of whole durian seed flour were high in protein, ash, fiber, and lipid compared to durian seed starch and demucilaged flour. Regarding functional properties, the whole durian seed flour still exhibited high water absorption capacity, peak viscosity, swelling power, and emulsifying capacity. Moreover, the recent study by Siti Faridah et al. (2021) reported on the physicochemical and thermal properties of durian seed flour. Accordingly, durian seed flour also exhibited the highest protein content and absorption capacity. In terms of thermal properties, if the flour has low viscosity, it's an indication that the following gelatinization will dissolve quickly.

The application of durian seed flour is not limited to baking products or substitute for other ingredients like a filler ingredient of meatballs, as stated in the study of Malini et al. (2016) but it has constituents that can be used and applied in non-food application. As stated in the study by Permatasari et al. (2021), durian seed flour has the potential to become a renewable source for the creation of eco-friendly plastics due to its high starch, gum content, and other trace components including protein and lipids, which are components of eco-friendly plastics.

The study of Malini et al. (2016), stated the process of making durian seed flour. The 35 g weight and good condition of the durian seeds have been used and they were then thoroughly washed. The cleaned seeds were peeled and given a 5-min soak in hot water. After that, the seeds were steeped in 10% calcium hydroxide (1 L of distilled water with 10 g of calcium) for an hour. To create dried seeds, the seeds were first sliced and then dried for 3–4 days. The dried seeds were eventually ground and sieved.

Edible film

Edible films, a promising innovation in the food industry, offer a sustainable and eco-friendly solution for food packaging and preservation. Edible films are plastics made from renewable resources and can be broken down by microorganisms (Wahidin et al. 2021). In the study of Sitti Rahmawati (2021), the edible film was achieved through the physical mixing process. To obtain edible film from durian seed, starch was extracted and then mixed with glycerol, plasticizer, and sorbitol to determine the characteristics. The findings indicate that the edible

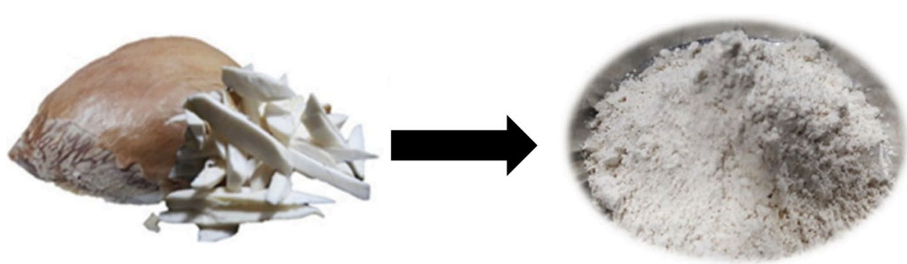


Fig. 5 Durian seed flour (Charoenphan & Kwanian 2018)

film has a shelf life of 5 days at room temperature and 7 days at cold temperatures. A biodegradability analysis was also conducted, and it took 7 days for the material to disintegrate. This demonstrates that the durian seed starch edible film is eco-friendly packaging.

In a separate investigation, the creators of an edible film from jackfruit and durian seeds were also employed to assess the transparency and thickness of the film. The findings of the comparison show that durian seed starch edible film had lower transmittance than jackfruit seed starch edible film for all starch concentrations. Since all films have extremely low transmission (below 23 percent at 550 nm), this opaque film can be used to package food that doesn't need to be transparent (Wahidin et al. 2021).

Bio-composite film

Biocomposite films have found extensive application in the food industry, primarily as food packaging materials, owing to their unique properties and eco-friendly nature. Using biodegradable materials as substitutes for single-use plastics can significantly reduce the production of small plastic items, which are typically not recycled due to their diminutive size and limited recycling capabilities (Alvarado et al. 2023). The attraction of bio-composite materials has been increasingly important due to their potential substitute for conventional materials used in the manufacturing industry (Yildizhan et al. 2018). Accordingly, bio-composite materials are composed of natural fibers or natural resins. The study by Timbangen Sembiring et al. (2018) stated that durian husk has an abundance of natural fibers as reinforcement for thermoplastic and thermoset to produce bio-composite materials. The commonly used for thermoplastic bio-composite material are polyethylene (PE), polyvinylchloride (PVC), polystyrene (PS), and polypropylene (PP). While thermoset are polyester, epoxy, phenol formaldehyde, and vinyl esters (Faruk et al. 2012). Generally, composite materials composed of matrix as a filler and binding agent as a reinforced material. The characteristics of bio-composite film provide a remarkable advantage such as being a biodegradable material, renewability, and sustainability (Yildizhan et al. 2018).

Various researchers reported the effectiveness of using during husk as a bio composite film in the application of active food packaging. The common approach to develop active food packaging is to blend with active compounds, such as antimicrobial and antioxidants (Ashrafi et al. 2018). These active compounds are present in the properties of durian husk. The incorporation of active compounds in food packaging helps to extend the shelf life while maintaining the quality of food products Anuar et al. (2018). According to Salgado et al. (2015) and Vodnar et al. (2015), using antimicrobial packaging provides greater benefits than just adding antimicrobial chemicals to food goods.

In preparation of bio composite film, Anuar et al. (2018) created bio composite film made of durian husk fibre through the process of solvent casting. The samples undergo by drying, adding plasticizing agent, and casting method. The results showed that the used of durian husk fiber is suitable for food packaging. Another study from Timbangen Sembiring et al. (2018) reported that the mechanical and physical properties of durian husk fibers composites are suitable for processing and blending with other biopolymer. It was also agreed by Nur Aimi et al. (2015) and Manshor et al. (2014) that durian husk has the properties into biopolymer with the incorporation of micro-sized durian husk and nano-sized filler in polypropylene (PP) and polylactic acid (PLA) composites.

Substrate of *Monascus* sp.

Monascus spp. is a type of fungus that has been used in Asia for many centuries as a natural color and flavor ingredient in food and beverages like Chinese cheese, bagoong, wine, tofu, sake, miso, pork, sausage, and fish (Abdul Manan et al. 2017). *Monascus* spp. produces red, orange, and yellow pigments during both submerged and solid-state fermentation (Srianta et al. 2019). In the study of Srianta et al. (2012a, b), the researchers utilized durian seeds to generate a substrate of *Monascus* spp. as a natural food colorant. Starch content and the proximate composition of the durian seeds were examined. It then underwent a chemical process to obtain moisture content and monacolin K which are needed for suitable angkak production. From the results, the durian seed has the potential to be employed as a novel substrate for the manufacturing of angkak. More study is needed to raise the monacolin K content and assess the functionality and safety of durian seed angkak.

For further study of angkak production from durian seeds, the said Monascus-fermented durian seed (MFDS) has evaluated antidiabetic and antihypercholesterol agent with in vivo method using Wistar rat (Nugerahani et al. 2017). The study revealed that the effect of administering MFDS suspension at doses of 0.05, 0.10, and 0.15 g/2 mL for 28 days had reduced blood glucose and cholesterol. In addition, higher levels of MFDS suspension are more effective at reducing rats' blood sugar and cholesterol levels. It also enhanced HDL cholesterol, LDL cholesterol, and triglycerides levels in the blood. However, the researchers also recommended that more research be done on the adverse effects of MFDS.

In another study by Srianta et al. (2014), the researchers evaluate the antioxidant activity of Monascus-fermented durian seed extracts. Using phosphomolybdenum reduction, FRAP, and DPPH radical scavenging, it was demonstrated that the MFDS had antioxidant activity. A fermented durian seed extract has been shown to have phytochemical benefits that make it a potential antioxidant food ingredient and help it regain its promising status in local traditional medicine.

Non-food applications

Biopesticides

Based on a study by Kusumaningtyas et al. (2019) durian husk extract can be used to create biopesticides (2019). Biopesticides contain a compound that is toxic to insect, pest and nematodes (cause plant diseases). Munarso, (2012) reported that biopesticides are biodegradable and easy to deteriorate. Based on phytochemical tests, durian husk contains chemical compounds that have biological activity (bioactive substances) (Setyowati et al. 2014). These biologically active compounds are secondary metabolites consisting of tannins, saponins, alcoholoids, triterpenoids and flavonoids (Azizah & Fitriani 2015; Hartini et al. 2018) which are toxic to pests. Thus, durian husk extraction is suitable and effective for biopesticides. In the study of Harahap et al. (2019), the authors combined the sirsak leaf and durian husk since these two has chemical content which is cytotoxic to insect pests. The generated biopesticides was tested on peach leaves and chili plants. The results showed that a natural biopesticide made from sirsak leaves and durian husk has an effective result in killing pests.

From the study of Kusumaningtyas and Armiano Syah (2020), biopesticide was achieved through the process of cleaning, boiling, drying, cutting, and filtering the liquid extract of durian husk. The extract was combined with 3 oz of smooth garlic, 1 pound salt, and 500 mL of water in a container. The mixture was well mixed until it was homogenous and fermented for three days in a closed container to generate biopesticides.

Biochars

Biochar is a carbon-rich material that can modify soil properties and enhance agronomic performance (Glaser et al. 2019). Many researchers have developed biochar from various agricultural waste sources such as banana peel, corn cob, mangosteen husk, durian husk, and rice husk (Takolpuckdee 2014), among others, for use in fertilization and soil amendments. With that, different methods were used for producing biochars and one of the methods is from the study of Prakongkep (2014), the biochar was created in a traditional kiln used by Thai farmers (Fig. 6). The process was initiated by burning the outer metal cylinder to heat biomass in the inner cylinder which is sealed off from the air. Then it was homogenized and ground for chemical analysis. The chemical properties present in durian husk biochar were high levels of potassium, calcium, magnesium, and phosphorus whereas silicon, sulfur, and aluminum are quite low. Based on the results, the potassium content of

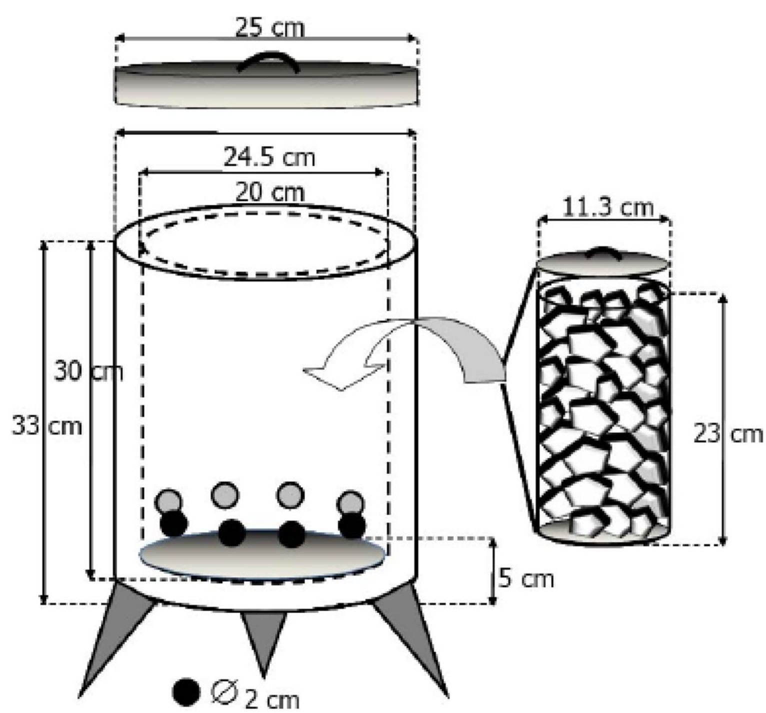


Fig. 6 Biochar is traditionally produced in traditional kilns at unregulated temperatures of 350 °C and low oxygen levels. (Prakongkep 2014)

durian husk biochar was very high because of the soluble potassium minerals which can be considered as a potential potassium fertilizer. The potassium minerals are soluble in water such as sylvite (KCl), kalicinite ($KHCO_3$), archerite (KH_2PO_4), chlorocalcite ($KCaCl_3$), and struvite ($KMgPO_4.6H_2O$). Moreover, Calcite ($CaCO_3$) was also present in durian biochar however this mineral has low water of solubility.

Another study is from Takolpuckdee (2014), the method used in this study is through the process of pyrolysis using the cylinder metal furnace type (Fig. 7) to produce biochar (Fig. 8). The cylinder metal furnace was securely sealed and burned with no oxygen once the waste material had been introduced. Then, the desiccator was filled with the prepared biochar and tightly sealed. The study used durian peel, banana peel, mangosteen husk, corncob, and shrimp shells as sample agricultural wastes. According to the findings, durian peel includes a significant amount of volatile compounds and water, while corncob has the lowest proportion. The chemical content presents in the biochar of each agricultural waste material were nitrogen, phosphorus, calcium, and magnesium. Among the agricultural waste, banana peel biochar has the highest percentage of biochar production. The highest heat of combustion was corncob biochar, while the highest nitrogen content is the shrimp shell biochar. Banana peel biochar had the greatest phosphorus content, shrimp shell biochar had the highest calcium content, and durian peel biochar had the highest magnesium level. The usefulness of the biochar product was also examined through the development of morning glory swamps.

Fig. 8 Biochars from durian husk. (Takolpuckdee 2014)

Adsorbent

Durian husk has the ability to capture water pollutants due to its cellulose, hemicellulose, and lignin content, as well as its macro-porous structure, resistance to temperature, pH, mechanical stress, and prolonged immersion in water. Activated carbon is commonly used for water treatment, but the materials used to make it are quite expensive, so Payus et al. (2020) proposed the use of durian husk as a low-cost adsorbent in water treatment. In the study, the process of obtaining an adsorbent from a durian husk is by cutting the durian husk into tiny pieces and then breaking it up and blending it with 2.0 L before being filtered, cleaned, and rinsed with distilled water. The remaining water molecules were then evaporated by drying them in the oven for 24 h at 100 °C. The durian husk was then modified in a jar test using 1 M NaOH for 24 h at room temperature and 200 rpm agitation. Adsorbents are modified with alkaline solutions like NaOH in order to change their surface functional groups, surface morphology, and textural characteristics, which will increase their ability to adsorb a specific adsorbate with greater selectivity.

Besides, there are some researchers who published articles that conducted a study about producing activated carbon out of durian wastes. From the studies of Mokhtar et al. (2013), Chandra et al. (2009), and Yuliusman et al. (2020), the researchers discussed the process of obtaining activated carbon from durian waste. Generally, cutting, cleaning, drying, and grinding is the basic process, and the chemical activation is then followed by adding KOH (Chandra et al. 2009; Mokhtar et al. 2013), and

Fig. 7 Pyrolysis Cylinder Chamber. (Takolpuckdee 2014)

H_3PO_4 (Yuliusman et al. 2020). To identify the best conditions for producing high surface area activated carbons from durian waste, several carbonization temperatures and impregnation proportions were used. According to Mokhtar et al. (2013), a study employing durian peel waste had positive results. It is a promising activated carbon since the best yield was obtained during the carbonization process, which takes place at 400 °C for four hours with a KOH concentration of 0.6 M. Yuliusman et al. (2020) also stated that as a result of this investigation, activated carbon with a surface area of 797.99 m^2/g was successfully manufactured and met the SNI requirement. According to Chandra et al. (2009), a KOH to durian shell ratio of 0.5 and an activation temperature of 773 K are the best conditions for producing high surface area activated carbon.

Hydrogel bandages

Hydrogel is outstanding in terms of water absorption ability and soft mechanical properties which is why it is widely used in cosmetics, drug delivery, tissue engineering, and wound dressing. It is highly utilized in wound dressing, implant coating, and infection treatment with physiological conditions that are favorable for bacteria growth due to the moist environment. In the study of Cui et al. (2021), the researchers used the high-purity cellulose of durian husk, which is used as a natural raw material for the production of water-based cellulose hydrogels. The study revealed that organo-hydrogel bandages can keep wound areas cooler and moister than traditional bandages, which can hasten the healing process. The created organo-hydrogels displayed no cytotoxicity and demonstrated strong antibacterial activity when used as a wound dressing on pig skin as a proof of concept. The novel proof-of-concept hydrogel bandage is applied similarly to those that are presently on the market by just placing it over the wound. Additionally, the team of Prof. William Chen, food scientists from Nanyang Technological University, Singapore (NTU Singapore), and the director of NTU's Science and Technology Programme, stated that the typical hydrogel bandages being sold in the market are made from synthetic materials and are costly compared to the new hydrogel made from natural waste materials. The professor also added that the hydrogel bandage produced is especially important for patients who are diabetic and suffer from chronic wounds (Kok, 2021).

Non-wood based raw material for the pulp and paper industry

Based on the findings of Masrol et al. (2018) the durian husk will be beaten as part of a chemical–mechanical pulping process. Chemi-mechanical pulp is simply a pulping process in which the fibrous materials are separated by combining three different techniques: chemical, mechanical, and thermal. The beating method is often used to enhance virgin paper that has not been beaten and is inappropriate for papermaking due to its poor strength, bulkiness, and surface roughness, as stated by Masrol et al. (2018). Additionally, another study by Masrol et al. (2015) indicated that in order to get better results, beating and bleaching must be considered for better outcomes as they may increase the pulp and paper qualities of the durian husks. In the process, the durian husk was cleaned and rinsed to remove any debris or residues. The durian husk cubes were then naturally dried for around 3–5 days in direct sunshine to minimize moisture content. According to reports, the drying of durian husk may be done inexpensively in the sun (Zddin & Risby 2010). Finally, the dried durian husks were kept at room temperature in an airtight container to avoid fungal infection and moisture absorption. First, a 6:1 ratio of liquid to material was used to treat the naturally dried durian husks for 2 h at room temperature using 10% sodium hydroxide (NaOH). The treated durian husks were rinsed with running water once the NaOH treatment was completed. The study revealed that raising the beating revolution has improved the durian husk chemical–mechanical pulp and paper's overall physical and mechanical qualities. The results also emphasize that the durian husk can be considered a promising alternative to non-wood-based raw materials for the paper industry, and also beneficial to the durian industry.

Bio-plate

The bio plate production process was based on the study of Tengrang et al. (2020). Fresh durian husk is the main component of the bio plate. The process begins with cutting the durian husk into 3 mm thick pieces and then drying it in an oven at 55 °C for 24 h. The dried durian husk was then undergone chemical treatment to extract the cellulose, the pre-form of the bio plate was prepared by dispersing the dry fiber into the water to form a slurry by Moulinex as 10 g of fiber:1 L of water ratio. The researchers used a hydraulic compression machine to manufacture a 7″ circular bio-plate under the pressure of 150 bars for 5 min at 150, 160, 170, and 180 °C. The mechanical and physical qualities were examined and compared with bio-plate from bagasse using Thai industry standards, JIS, ASTM, TAPPI, and ISO. The study revealed the possibility of utilizing the residue of durian to create bio plates, especially the husk fiber that has undergone bleaching. Aside from durian husk, a durian seed could also be used as a main component to create a bio plate. A study from Srisang and Srisang (2020) investigated the use of durian seed mixed with poly (lactic acid) PLA for bio plate production. After the brown covering of the durian seed was peeled off, the harvested seeds were dried. The specific ratio between the mixture of durian seed and PLA was stated before undergoing compression at temperatures of 90, 110, and 130 °C with pressures of 2.0, 2.7, and 3.4 MPa. By using the compression process, durian seed and PLA were successfully made into bio plates. These manufacturing conditions for the bio plates provided low water absorption, high tensile strength, and adequate disintegration in 7 days.

Liquid smoke

According to Faisal et al. (2018), the major components of liquid smoke are cellulose, hemicellulose, and lignin, which are found in durian peel. Liquid smoke is a flavoring agent created by burning wood chips, collecting the smoke, and condensing it in a liquid solution (Sedghi 2022). Because of the presence of antimicrobial substances, liquid smoke can be utilized for natural food preservation (Permanasari et al. 2020). Two key chemicals are phenol and acetic acid.

The process stated in this section is adapted from the study of Faisal et al. (2018), where the researchers studied the liquid smoke produced by pyrolysis of banana peels at a low temperature. The liquid smoke was produced in a 5 kg stainless-steel pyrolysis reactor. The samples of Durian husk were acquired from various sellers and weighed to establish their fresh weight. As raw materials, 3 kg of dry outer and inner peel were placed into the reactor, and the samples were paralyzed at 300 °C, 340 °C, and 380 °C. Grade 3 liquid smoke, tar, and charcoal were created by the condensed smoke. The liquid smoke was analyzed using gas chromatography-mass spectrometry (GCMS-QP2010, Shimizu) and high-performance liquid chromatography (HPLC, Hitachi L-4200H). Based on the findings, liquid smoke formed from durian peel has the potential to be used as a natural food preservative as well as a biopesticide due to the presence of phenol and acetic acid.

Bio-ethanol feedstock

Bioethanol production provides a good promise to obtain fuel production that is renewable and sustainable (Sebayang et al. 2017). Production of bioethanol from durian husk is being investigated by Irhamni et al. (2018), the durian shells are fermented into bioethanol, with a maximum ethanol level in the water of 16.69%. At 2,163 min, the greatest peak of the chromatogram reached 96.99%, indicating that it was the first peak of bioethanol.

Furthermore, liquefaction and saccharification processes were also used in the study of Soeprijanto et al. (2020). In the study, a batch reactor was used to produce bioethanol. To produce reducing sugar, liquefaction and saccharification were carried out in two steps. In the liquefaction, in an Erlenmeyer 2 litter, 200 g of durian peel flour, α-amylase, and water were combined. The mixture was then heated at 90 °C for two hours. While in saccharification, the mixture mentioned was heated at 60 °C for 4 h. The sugar produced was then fermented by adding up to 0.2% yeast, 0.5% urea, and 0.5% KH_2PO_5 to the quantity of reduced sugar obtained. The bioethanol was produced at 78 °C after fractionated distillation of the fermentation. The study found that following fractionated distillation, 95% of the bioethanol was recovered. It has been determined that durian husks work very well as an alternative fuel and that the husks are both naturally renewable and suitable for use in motor vehicles.

Aside from durian husk, durian seed is also utilized in producing bioethanol which is investigated by Sebayang et al. (2017). It is produced by utilizing the ultrasound technique in its enzymatic hydrolysis process to yield a favorable reducing sugar concentration. As a result, the ethanol produced by fermenting was then delivered to an ultrasonic-assisted enzymatic hydrolysis process to reduce sugar. According to Barcelos et al. (2011), decreasing particle size reduced the effect of diffusion restriction and resulted in a greater sugar yield when compared to larger particle sizes. The durian seeds were dried so that they could be stored at a temperature of 25 °C for extended periods of time.

Additionally, Masturi et al. (2020a, b) and Seer et al. (2016) produce bioethanol through fermentation by Saccharomyces cerevisiae yeast. Though the study of Seer et al. (2016) used mixed cassava and durian seeds, the study revealed that durian seeds can be more efficient for bioethanol production than the traditional feedstock like cassava, because it produces a higher amount of fermentable sugar than cassava powder.

Other methods in the utilization of durian husk

In current days, durian waste has been used to make bio-based products. As mentioned earlier, the durian husk consists of 60.45% cellulose, 15.45% lignin, and 73.67% pectin (Haseem et al. 2019), and the durian seeds obtained a search of approximately 46.2%, which is stated in the study of Hardiyanti et al. (2021) and Rahayu et al. (2019). The cellulose, lignin, pectin, and starches can be converted into valuable products like cellulose, which can be turned into nanocellulose via chemical and mechanical methods. Nanocellulose has been prominent in recent days because of its capability to be applied to food and non-food applications. As a result, numerous studies have been conducted to determine the potentialities of durian husk nanocellulose.

Overview of cellulose nanoparticles

Nanocellulose can be used in a variety of applications, including composite materials, filters, packaging, biomedical products, military, energy, and cosmetics (Aimi et al. 2015); (Ilyas et al. 2021). Additionally, nanocellulose is becoming increasingly important in the food packaging industry, owing to its environmentally friendly and sustainable production from agricultural waste. Accordingly, there are three types of nanocellulose that are applicable for packaging films: cellulose nanofiber (CNF), cellulose nanocrystals (CNC), and bacterial nanocellulose (BNC) (Nordin et al. 2017). Cellulose nanofibers (CNFs) have the characteristics of natural cellulose, such as easy biodegradability, low density, and reproducibility, as well as outstanding properties such as a high surface-area-to-volume ratio, excellent tolerable mechanical properties, a high gas barrier property, and a low coefficient of thermal expansion (Du et al. 2016). Cellulose nanofiber (CNF) has amorphous crystallinity which is good for mechanical stiffness and strength. However, its length is too short to be used for environmentally friendly structural composite fibers. Cellulose Nanocrystalline (CNC) is a dependable filling agent widely used in the food packaging, pharmaceutical, automotive, aerospace, and construction industries. Furthermore, nanocrystalline cellulose has received a lot of attention for its use in a variety of applications ranging from advanced biomedical materials to food packaging materials due to its exceptional physical and biological characteristics such as high crystallinity, large specific surface area, high aspect ratio, good mechanical properties, high thermal resistance, the abundance of surface hydroxyl groups, biodegradability, low toxicity, and biocompatibility (Ilyas et al. 2021).

Moreover, bacterial nanocellulose (BNC) is a nanofibrillar polymer with distinct properties such as high chemical purity, flexibility, absorbency, flexibility, and mechanical strength. The three types of nanocellulose are highly potential for the application of packaging film. However, some researchers demonstrated that cellulose nanocrystals are an appealing material to incorporate into composites because they can provide additional strength gains while also providing highly versatile chemical functionality.

Extraction of cellulose and nanocellulose from durian husk

Moon et al. (2011) found that separating cellulose particles from cellulose source materials is accomplished in two stages. The first stage involves purifying and homogenizing the source material to react more reliably in future treatments. The second stage is the separation of these "purified" cellulose elements into their microfibrillar and crystalline components.

In the study of Penjumrasa et al. (2014), the extraction of cellulose from durian husk undergoes two steps. The first step is the production of holocellulose using the chlorination method or bleaching process. The second step is to convert the holocellulose to cellulose using mercerization at room temperature. The result shows that the color was changed from brown to white when it underwent those processes. Additionally, the diameter represented is in the region of 100–150 m. The aspect ratio is 20–25, which is greater than the minimal aspect ratio value for good strength transfer in any reinforcing material. These methods were adapted by Lubis et al. (2018)and Rahman et al. (2016) with slight modifications. This cellulose that was obtained shares properties with cellulose that was obtained from other sources, including hemp, sisal, cotton, bananas, etc.

As mentioned, nanocellulose can only be achieved if the cellulose will go through mechanical and chemical treatment. There are two primary techniques for making nanocellulose, and these are the top-down and bottom-down approaches (Etuk et al. 2018).

Top-down approach

There are three subcategories in a top-down approach, namely mechanical, chemical, and mechanical-chemical methods which are shown in the (Table 3) below.

Bottom-Up approach

The idea of Bottom-Up approach can be defined as assemblage procedures in which components at atomic and molecular scales are stacked on top of one another to produce nanofibers that are relatively uniform and consistent (Etuk et al. 2018). Electrospinning and bacterial biosynthesis are examples.

Electrospinning Electrospinning is a simple and efficient method to create polymer membranes with completely linked pore configurations and micron-sized fibers. An electrohydrodynamic process is used in electrospinning (Prasanth et al. 2015). A liquid droplet is electrified to create a jet during this process. Stretching and elongation are then used to produce fibers (Xue et al. 2019).

An electrospinning system is made up of four main parts (Fig. 9): a syringe pump, voltage power supply, a needle, and a collector (Rim et al. 2013). As a result, a syringe pump regulates the polymer solution's flow rate. The voltage power supply, the needle that shifts the charged polymer solution into the high electric field, and finally a collector, such as a metal screen, plate, or rotating mandrel, that collects electrospun nanofibers are what provides the force to stretch the charged polymer solution into a fiber form.

Table 3 The extraction methods of nanocellulose using top-down approach

Method	Type of Extraction	Extraction process	Reference(s)
Mechanical	High-pressure homogenization process	It entails utilizing force to drive a cellulose pulp into a vessel through a very small nozzle using a piston under high pressure and then subjected to a pressure drop to atmospheric conditions upon exiting the valve, resulting in significant shear stresses on the fiber surface.	PothulaLalithaKumar et al. (2016); Kargarzadeh et al. (2017); Etuk et al. (2018)
	Grinding	High energy input is necessary to decrease small particles with mechanical force to even smaller sizes. The cellulose slurry is repeatedly transferred between a static husking stone and a rotating husking stone spinning at around 1500 rpm until the necessary dimensions in the nano-range are reached and further size reduction is no longer possible.	PothulaLalithaKumari et al. (2016); Khalil et al. (2014); Etuk et al. (2018)
	Sonication	It is a method of agitating particles or discontinuous fibers in a liquid by using sound energy; because ultrasonic frequencies (more than 20 kHz) are commonly employed, the technique is also known as ultrasonication. Ultrasonic waves are produced in a liquid suspension by either directly sonicating the suspension with an ultrasound probe or "horn" or by submerging the sample container containing the suspension in a bath of an ultrasonic-wave-propagating liquid (indirect sonication).	Chung D. (2016); Sandhya et al. (2021); Taurozzi et al. (2012)
	Microfluidization	The microfluidizer, unlike the homogenizer, functions at a constant shear rate rather than a constant pressure. To increase pressure, an intensifier pump is employed, and an interaction chamber is employed to defibrillate the fibers by providing shear and impact pressures against colliding streams and channel walls.	Kargarzadeh et al. (2017); Khalil et al. (2014); Kaur et al. (2021)
	Cryo-crushing	Cryocrushing is an alternative method for producing nanofibers in which fibers are frozen using liquid nitrogen and high shear forces are then applied. Cellulosic fibers are soaked in liquid nitrogen before being shattered with a crusher and pestle. A standard cryo-crusher has two husking stones, a stator, and a rotor that can rotate at 1500 rpm.	Chirayil et al. (2014); PothulaLalithaKumari et al. (2016); Frone et al. (2011); Kargarzadeh et al. (2017); dos Santos et al. (2016); Etuk et al. (2018)
Chemical	Acid hydrolysis	In the process of acid hydrolysis, the amorphous portions are typically hydrolyzed, whilst the crystalline parts remain unaffected by the acid treatment. This characteristic is caused by the crystalline areas' high tolerance to acid treatment than the amorphous parts.	Chen et al. (2019); dos Santos et al. (2016); Onu and Mbohwa (2021)
	Alkali Hydrolysis	Similar to acid hydrolysis, alkali hydrolysis involves an enzymatic attack on amorphous areas of the cellulose substrate while staying in the crystalline sections. These treatments are typically performed with diluted NaOH (1–10%) concentrations at low or high temperatures, and concentrated NaOH solutions above 10% at low temperatures only. In rare cases, NH_4OH and anhydrous NH_3 (gas or liquid) are also used to activate organic molecules, resulting in an increase in hydrolytic breakdown.	Hubbe et al. (2008); Hua et al. (2016); Frone et al. (2011)
	Enzymatic hydrolysis	Enzymatic hydrolysis involves the employment of enzymes to aid the breaking of bonds in organic molecules, which is followed by the addition of water molecules. These enzymes are fungal in origin and are known as cellulase in the case of cellulose.	dos Santos et al. (2016); Etuk et al. (2018); Madhu (2022)
Mechanical-chemical		The chemical–mechanical method combines one or more chemical pretreatment procedures with mechanical disintegration techniques.	Etuk et al. (2018)

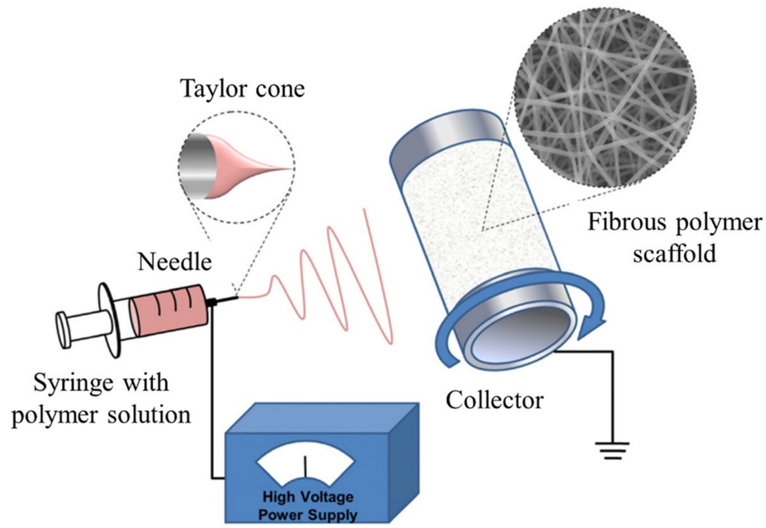


Fig. 9 Basic setup for an electrospinning apparatus scheme. Adapted from the study of Rim et al. (2013)

Current status of commercializing durian waste products

Currently, the commercialization of durian waste products remains relatively underexplored. However, there have been notable ventures in this regard. For instance, in Davao City, Philippines, durian waste has been ingeniously transformed into handmade paper albums (Phoung 2012). This initiative is an extension of the Women and Appropriate Technology Program of the Women Development & Technology Institute (WDTI) National Office, primarily focused on empowering women to augment their income beyond farming activities. With consistent client orders, individual women have the potential to earn an average of 700 to 1000 pesos per week. Furthermore, a groundbreaking product derived from durian waste was recently showcased at Malaysia's National Research Expo 2022 (Malone 2022). This expo served as a platform to present research outcomes with significant practical potential. The research team has embarked on a series of product development endeavors, including the creation of biodegradable foam packaging, durian peel paper, and even furniture material. The critical role of product concept testing in assisting communities or individuals aiming to develop durian peel items was underscored during this event, marking a significant step towards the diversification of durian peel products and their promotion as distinctive local souvenirs.

Future prospects

The world is continuously producing waste which has in turn inspired researchers in the direction of green raw materials for diverse applications. The development of products from agricultural waste encourages future researchers to create more innovation. This will contribute more to our economic development while reducing the waste problem in our environment. Moreover, the unique composition of durian waste can provide many future products in the agricultural sector, especially in food and non-food industries. Nowadays, there's a lot of product development related to the utilization of cellulose in durian husk, mainly in the food packaging industry. Thus, it is encouraged to utilize the pectin and lignin from the durian husk which obtained excellent potential for product development.

Conclusion

The rate at which landfills are being loaded is increasing, especially because of the massive amount and size of durian waste, which requires more space to dispose of. That's why it is certainly important to utilize this waste where it is beneficial and can contribute to the agricultural sector, food, and non-food industries. The waste from durians is frequently burned or dumped into landfills, which pollutes the environment. The strategic approach for handling durian waste is by upgrading this waste into numerous useful goods, making efficient waste management of the durian husk essential. The waste of durian contains nutritional values that provide great potential for valorization. It has been stated in this review the potentialities of durian waste along with its utilization methods, therefore, it has been proved that durian waste should not be thrown away because it possesses great potential in terms of value-added products.

Acknowledgements
The authors are thankful to the Department of Agricultural and Biosystems Engineering (DABE), College of Engineering and Geosciences, Caraga State University (CSU), Ampayon Butuan City 8600, Philippines and also to the Center for Resource Assessment, Analytics, and Emerging Technologies (CReATe) under Value Adding of Agricultural Wastes Project for the guidance and technical expertise offered during the writeup of this review article.

Authors' contributions
Beggie Gamay and Patricia Botecario carried out the literature review and initially drafted the manuscript. Philip Donald Sanchez and Marjun Alvarado conceptualized, criticized, and revised the manuscript.

Funding
Not applicable.

Availability of data and materials
All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors confirm that they have no known financial conflicts of interest or close personal connections that would affect the outcome described in this review study.

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Received: 4 August 2023 Accepted: 5 November 2023
Published: 26 February 2024

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