

Bioactive compounds of durian (*Durio* spp.) shells, their quantitative methods, and possible values in the foods and pharmaceutical industries: a review

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ABSTRACT: The aim of this review was to comprehensively explore the bioactive components of durian (*Durio* spp.) shell, focusing on their quantification and potential applications in the food and pharmaceutical industries. Durian shells, often considered a waste by-product of durian fruit cultivation, have garnered increasing interest due to its rich composition of bioactive compounds, including polyphenols, flavonoids, fiber, and other antioxidants. These compounds exhibit a wide range of biological activities, such as antioxidant, anti-inflammatory, and antimicrobial properties, suggesting the potential for significant health benefits. The method for reviewing was exploring existing literature in the past ten years to provide an in-depth analysis of the chemical composition of durian shells, identifying key bioactive components and their roles in enhancing human health and preventing chronic diseases. The results showed a variety of valuable compounds can be found and extracted from durian shells, including pectin, cellulose, polyphenols, flavonoids, flavonols, and phenolic acid, etc. And through a thorough examination of the various quantification techniques for those bioactive compounds, high-performance liquid chromatography, spectrophotometry, and colorimetric assays, with a focus on their ability of precise measurement, are proven to be essential for validating the nutritional and pharmacological claims of durian shells as a functional ingredient in food and pharmaceuticals. Additionally, durian shell's bioactive compounds can be harnessed as natural preservatives in food products, offering a sustainable alternative to synthetic chemicals. Furthermore, the antimicrobial and antioxidant properties of these compounds make durian shell a promising candidate for use in pharmaceutical formulations, such as dietary supplements, topical agents, and therapeutic treatments for various conditions. This review contributes significantly to the scientific understanding of durian shell as a sustainable resource, emphasizing its underutilized potential in enhancing food safety, functional nutrition, and pharmaceutical innovations.

KEY WORDS: *Durio* spp., shell waste, bioactive compounds, therapeutic potentials

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I. INTRODUCTION

Durian (*Durio* spp.), one of the most unique and culturally significant fruits in Southeast Asia, is mainly prized for its unique aroma and flavor. It is predominantly cultivated in countries such as Vietnam, Thailand, Malaysia, and Indonesia, with global production steadily increasing due to growing demand both locally and internationally [1]. In general, durian holds a special place in local economies, contributing significantly to the agricultural sector through both export and domestic consumption. However, along with the

increasing consumption of durian, the issue of agricultural waste, particularly in the form of durian shells, has become a pressing concern. The edible portion of durian constitutes only about 15–30% of the entire fruit, with the remaining mass being non-edible waste, including the shell, seeds, and husk. Durian shells, which account for up to 60% of the fruit's total mass, are typically discarded after consumption, leading to substantial amounts of organic waste being generated each year. With large-scale durian farming, this waste becomes a major environmental concern, as improper disposal methods, such as open burning or landfilling, contribute to air pollution, greenhouse gas emissions, and land degradation.

Current approaches to manage durian's shell waste are limited, with much of it still ending up in landfills [2]. While certain efforts have been made to utilize durian waste as fertilizers or as a low-cost feedstock for bioenergy production, these practices remain underdeveloped and inefficient at a large scale. The high volume of durian shell, combined with its slow degradation in nature, underscores the need for more sustainable solutions to deal with this organic byproduct. Amid the growing global emphasis on sustainability, there is increasing interest in the valorization of agricultural wastes, including durian shells. The concept of waste valorization refers to the process of transforming waste materials into valuable products, thus reducing the environmental burden and adding economic value. In the case of durian shells, emerging research suggested that they are an abundant source of bioactives, such as cellulose, pectin, flavonoids, polyphenols, and phenolic acids which hold potential for applications in health, wellness, and various industries. However, in-depth information regarding those valuable compounds, their quantities, and possible applications, is still scattered, thus, possesses such limitations in the field of shell waste's utilisation and recycling.

Therefore, this review explores durian shells' bioactive compounds and other useful matters in the context of therapeutic potential, their roles and potential as key materials in some promising industries, including food and pharmaceutical ones, together with their quantities and quantitative methods. The review mainly exploits the side of value in the utilisation of durian shells in terms of their compositions. It consolidates research on the chemical compositions, highlighting cellulose and pectin; flavonoids, polyphenols, and phenolic acids and their health benefits, such as antioxidant and antimicrobial activities. Industrial uses, including cellulose-based bio composites and biodegradable products, are discussed, alongside applications in biotechnology like biofilms and drug delivery systems. Safety concerns regarding toxins and allergens, as well as environmental issues from improper disposal, are addressed. The review advocates for sustainable green extraction methods and further research into durian shell utilization.

II. VALUES OF DURIAN SHELLS IN FOOD AND PHARMACEUTICAL INDUSTRIES

2.1 Therapeutic properties and health benefits of durian shells

2.1.1 Antioxidant properties

Durian shell, often regarded as agricultural waste, are rich in polyphenols, which play a crucial role in neutralizing free radicals in the body. These bioactive compounds possess a variety of health-promoting properties, particularly their ability to mitigate oxidative stress, which is implicated in numerous chronic diseases, including cancer, diabetes, and cardiovascular disorders [3]. The antioxidant capacity of durian shell extracts has been demonstrated in various studies, where they effectively scavenge reactive oxygen species (ROS) and reduce lipid peroxidation. This property positions durian shell as a promising candidate for use in nutraceuticals and functional foods, where the incorporation of natural antioxidants can enhance the health benefits of food products. The potential for developing health supplements that utilize durian shell extracts could meet the growing consumer demand for functional foods that support overall well-being.

2.1.2 Anti-inflammatory and anti-microbial properties

The anti-inflammatory and antimicrobial properties of durian shells are of significant interest in both traditional and modern medicine [4]. Various compounds found within the shell exhibit anti-inflammatory activity, making it a valuable ingredient in formulations aimed at reducing inflammation and promoting healing. Research has shown that extracts from durian shells can inhibit the production of pro-inflammatory cytokines, thereby alleviating conditions associated with chronic inflammation. Furthermore, the antimicrobial properties of durian shell extracts have been documented, demonstrating effectiveness against a range of pathogenic bacteria and fungi. These characteristics open avenues for applications in wound healing and skincare products, where durian shell extracts can be incorporated to enhance healing, reduce infections, and promote skin health.

2.1.3 Dietary fiber and gut health

Durian shell is notably high in cellulose, a type of dietary fiber that offers numerous health benefits. The consumption of dietary fiber is widely recognized for its positive impacts on digestive health, aiding in regular bowel movements and preventing constipation. Additionally, the high fiber content in durian shell can contribute to weight management by promoting satiety, thereby reducing overall caloric intake [3]. The

fermentation of fiber in the gut also supports the growth of beneficial gut bacteria, which is linked to improved metabolic wellness and a reduced risk of various chronic diseases, such as obesity and diabetes [5]. Incorporating durian shell into food products could thus serve as an innovative approach to enhancing dietary fiber intake and supporting gut health.

2.1.4 Potential in cancer prevention and chronic disease management

Preliminary studies have indicated that bioactive compounds found in durian shells may play a role in cancer prevention and chronic disease management. The antioxidant properties of these compounds help combat oxidative stress, which is a known contributor to the development of cancer and other chronic diseases [6]. Some research has suggested that certain extracts from durian shell can inhibit the proliferation of cancer cells and induce apoptosis, or programmed cell death, in specific cancer types. These findings warrant further investigation into the mechanisms underlying these effects and the potential for durian shell extracts to be integrated into dietary strategies for cancer prevention and the management of oxidative stress-related diseases. Continued research in this area may uncover novel therapeutic applications and enhance the understanding of durian shell's role in promoting health and preventing disease.

2.2 Possible applications of durian shells in various industries

2.2.1 Cellulose extraction and utilization

The extraction and utilization of cellulose from durian shell presents significant opportunities for various industrial applications. As a renewable resource, cellulose can be converted into biodegradable materials, addressing the growing concern over plastic pollution. The development of biodegradable packaging and paper products from durian shell cellulose aligns with sustainable practices and consumer preferences for environmentally friendly alternatives [7]. Additionally, microcrystalline cellulose (MCC) derived from durian shells can serve as an excipient in pharmaceutical formulations, providing essential properties such as binding, bulking, and controlled release of active ingredients [8]. The versatility of cellulose extraction from durian shells underscores the potential for waste valorization in the durian industry.

2.2.2 Applications in biotechnology

In the realm of biotechnology, durian shell components have demonstrated considerable promise for innovative applications. The production of biofilms and hydrogels from cellulose can lead to advancements in medical and environmental sectors. These materials have potential uses in wound dressings, drug delivery systems, and tissue engineering, where their biocompatibility and biodegradability are critical. Moreover, nano-cellulose derived from durian shells offers unique properties that can be exploited in drug delivery systems, enhancing the efficacy and targeted delivery of therapeutic agents [9]. The utilization of durian shell components in biotechnology not only promotes sustainability but also paves the way for cutting-edge applications in healthcare.

2.2.3 Cosmetics and personal skincare

The antioxidant and anti-inflammatory properties of durian shell make it an attractive ingredient in the cosmetics and personal care industry. Formulations that incorporate durian shell extracts can benefit from enhanced skin health, as these extracts can help protect the skin from oxidative damage and inflammation [10]. Research into the potential of durian shell in skincare products suggests that it may improve skin hydration, elasticity, and overall appearance. Additionally, the use of natural ingredients like durian shell aligns with the growing trend toward clean beauty products, catering to consumer demand for effective and environmentally friendly skincare solutions.

III. POTENTIALLY VALUABLE COMPOSITIONS IN DURIAN SHELLS AND THEIRS QUANTITATIVE METHODS

3.1 Pectin

3.1.1 Profile and applications

Durian shells are a rich source of pectin, a valuable polysaccharide with various industrial applications. In the food industry, it is widely used as a gelling, stabilizing, and thickening agent in products like jams, jellies, and yogurts [11]. In the pharmaceutical sector, pectin's biocompatibility and ability to form gels enhance its use in drug delivery systems and wound dressings. Its biodegradable nature also makes pectin a suitable ingredient in environmentally friendly packaging materials. Beyond food and pharmaceuticals, pectin's film-forming capacity is beneficial in cosmetics and textiles, providing thickness and stability to products.

Pectin is a complex carbohydrate primarily composed of galacturonic acid units linked by α -1,4-glycosidic bonds [12]. It contains regions of linear “smooth” homogalacturonan and “hairy” rhamnogalacturonan, the latter of which includes side chains of neutral sugars like rhamnose, arabinose, and galactose. These structural features contribute to pectin’s unique properties, such as its gelling ability and water-holding capacity, which vary based on the degree of methylation of the galacturonic acid residues. High-methoxyl pectins (HMP) form gels in the presence of high sugar concentrations and acidic conditions, while low-methoxyl pectins (LMP) can form gels in the presence of divalent cations like calcium, making them ideal for different applications.

3.1.2 Quantitative methods

For the quantification of pectin content in durian shells, several analytical methods are commonly employed. Colorimetric analysis is widely used, where the uronic acid content in pectin is measured using a reagent such as carbazole or m-hydroxydiphenyl, producing a color change that can be quantified spectrophotometrically. The colorimetric method determines pectin content by measuring unreacted copper ions after their reaction with pectin to form copper pectate. The absorbance of residual copper ions is measured spectrophotometrically, providing an indirect calculation of pectin. The method is accurate, repeatable (2.09% RSD), eliminates the need for weighing, and is validated with commercial pectin and various plant types [13].

Another popular method is Fourier-transform infrared (FTIR) spectroscopy, which provides insights into the functional groups present in pectin by identifying characteristic absorption peaks for carboxyl and ester groups, confirming its purity and structural characteristics. Pectin was extracted from durian rind powder using acid extraction and alcoholic precipitation techniques, yielding approximately 0.13–0.71 g per 100 g of dried powder, equivalent to a 0.46% yield. FTIR spectroscopy confirmed the presence of O-H groups at 3327.83 cm^{-1} , indicating the pyranose ring structure characteristic of pectin [11].

High-performance liquid chromatography (HPLC) is also used for detailed profiling of the monosaccharide composition after pectin hydrolysis, which is essential for evaluating the quality and structural complexity of pectin. Gravimetric methods involve precipitating pectin with alcohol, typically ethanol, from an aqueous extract of the plant material, followed by drying and weighing the precipitate to determine pectin content quantitatively. HPLC was highlighted as a precise method for analyzing pectin by identifying and quantifying its monosaccharide and uronic acid components after hydrolysis. Using optimized conditions with specific detectors (e.g., UV, RI), HPLC ensures accurate separation and quantification of pectin’s structural elements. This versatile technique is widely applied to pectin from plant matrices, food by-products, and agricultural wastes [14].

3.2 Cellulose

3.2.1 Profile and applications

Durian shell has attracted considerable attention due to its high cellulose content [15]. Cellulose derived from durian shell presents a promising resource for various industrial applications, particularly because of its relatively high abundance and its potential to be a sustainable raw material. Additionally, the presence of cellulose in durian shell makes it an important material from agricultural waste for biorefining processes, where cellulose can be transformed into useful products such as bioethanol or other bio-based chemicals. Given the growing emphasis on sustainable materials, utilizing durian shell cellulose aligns with the shift towards circular economy models, where agricultural waste is repurposed to reduce environmental impact.

Structurally, cellulose is a linear polymer composed of β -D-glucose units linked by β -1,4-glycosidic bonds, which form long, unbranched chains that aggregate into microfibrils [16]. These microfibrils give cellulose its rigid structure and mechanical strength, making it a key component in the structural integrity of plant tissues. The characteristics of cellulose, including its insolubility in water and its resistance to degradation by most enzymes, are due to the extensive hydrogen bonding between adjacent polymer chains. In industrial applications, cellulose is widely used in the production of paper, textiles, and biofuels. Its biocompatibility and biodegradability also make it an attractive material for use in pharmaceuticals, food packaging, and environmental technologies, such as water filtration and bioplastics.

3.2.2 Quantitative methods

Several methods are available for the quantitative determination of cellulose in plant materials, including durian shell. One widely used method is the chemical analysis of cellulose content, where the sample is subjected to an acid hydrolysis process to remove non-cellulosic components, e.g. hemicellulose and lignin, and the remaining cellulose is quantified gravimetrically or through colorimetric assays [17]. Another common approach is the near-infrared spectroscopy (NIR), which allows for the non-destructive estimation of cellulose content by analyzing the absorbance of light at specific wavelengths associated with cellulose’s molecular

vibrations. A recent study demonstrated that UV-VIS-NIR spectroscopy is a rapid, non-destructive method for authenticating and analyzing the composition of cellulose films, offering an efficient alternative to traditional quality control methods [18].

FTIR is also employed to assess the structural features of cellulose in plant materials by detecting characteristic absorption bands corresponding to hydroxyl groups and glycosidic linkages in cellulose chains. Cellulose was extracted from durian rind by delignifying with acidic sodium chlorite, followed by mercerization using 17.5% sodium hydroxide. The extracted cellulose had a density of 1.59 g/cm³, as measured by a gas pycnometer. FTIR analysis confirmed the removal of non-cellulosic materials, while scanning electron microscopy (SEM) images showed that surface impurities were successfully removed. The cellulose fibers had a diameter of 100–150 µm and an aspect ratio of 20–25, suitable for reinforcement applications [15]. Furthermore, a more recent method involves the use of enzymatic hydrolysis where cellulase enzymes break down cellulose into glucose, and the glucose is then measured using HPLC. Durian shell acid hydrolysate was used as a substrate for bacterial cellulose (BC) production, and the metabolism of its components was analyzed by HPLC. The hydrolysate mainly contained cellobiose, glucose, xylose, formic acid, and acetic acid, with xylose being the predominant sugar, indicating efficient hemicellulose degradation [19].

3.3 Polyphenols

3.3.1 Profile and applications

Besides two key components mentioned in the previous sections, durian shell is increasingly recognized for its significant polyphenol content, which holds numerous potential benefits for both human health and various industries [20]. They are known for their potent antioxidant properties, which arise from their ability to donate hydrogen atoms or electrons to neutralize free radicals. This antioxidant capacity makes them valuable in promoting human health, as oxidative stress is linked to the development of chronic diseases such as cancer, cardiovascular diseases, and neurodegenerative disorders. Additionally, polyphenols exhibit anti-inflammatory effects by modulating inflammatory pathways and reducing the production of pro-inflammatory cytokines. The antimicrobial properties of polyphenols also contribute to their use in food preservation, where they help to prevent microbial spoilage and extend shelf life. In the pharmaceutical industry, polyphenols are explored for their potential in developing therapies for diseases linked to oxidative damage and inflammation. The cosmetic industry also utilizes polyphenols in skincare formulations for their ability to protect skin cells from photoaging and to support skin health by reducing oxidative damage.

Polyphenols are a group of naturally occurring compounds in plants, characterized by multiple phenolic rings [21]. They are classified into several groups, including flavonoids, phenolic acids, tannins, and lignans, with each type contributing specific properties based on its structure. Polyphenols are essential for the plant's defense mechanisms, protecting against oxidative stress, pathogens, and ultraviolet radiation. In durian shells, polyphenols play a similar protective role and are found in substantial amounts, making the shell a promising source of these valuable compounds.

3.3.2 Quantitative methods

The quantification of polyphenols in durian shell and other plant materials is essential for assessing their potential use and quality. One common method for determining polyphenol content is the Folin-Ciocalteu assay, which involves a colorimetric reaction where polyphenols react with the Folin-Ciocalteu reagent, producing a color change measured spectrophotometrically. A rapid microplate-based Folin-Ciocalteu assay for quantifying polyphenols was introduced by measuring the blue complex formed with the reagent at 765 nm. This miniaturized method is efficient, reducing reagent use and enabling high-throughput analysis with excellent precision. It is ideal for analyzing polyphenols in plant extracts and natural products [22].

HPLC is another preferred technique, allowing for the separation, identification, and quantification of individual polyphenol compounds, which provides a detailed profile of the polyphenol composition. Additionally, UV-Vis spectrophotometry is frequently employed in combination with solvents that selectively extract polyphenols; it measures absorbance at specific wavelengths associated with phenolic structures, enabling quantification based on a standard curve of a known polyphenol. A recent study on the determination of polyphenol content in red wines applying HPLC and spectrophotometric methods quantified individual polyphenols, such as catechin (10.6 to 20.5 mg.L⁻¹), quercetin (1.5 to 4.6 mg.L⁻¹), gallic acid (12.0 to 15.3 mg.L⁻¹), and caffeic acid (6.1 to 9.8 mg.L⁻¹), providing detailed profiles of these compounds [23]. In contrast, the spectrophotometric Folin-Ciocalteu assay measured total polyphenol content, ranging from 580 to 850 mg.L⁻¹, by quantifying all polyphenolic compounds, including those not detected by HPLC. The spectrophotometric method consistently reported higher polyphenol levels, reflecting its broader scope, while HPLC provided specific data on key compounds.

3.4 Flavonoids and flavanols

3.4.1 Profile and applications

Durian shell has emerged as a valuable source of flavonoids and flavanols, which are potent bioactive compounds with significant health benefits and industrial applications. Flavonoids are a large class of polyphenolic compounds with a basic structure consisting of two aromatic rings connected by a three-carbon bridge, forming a heterocyclic ring [24]. Within the flavonoid family, flavanols (also known as flavan-3-ols) are a specific subgroup characterized by a hydroxyl group on the third carbon of the C-ring. Common flavanols include catechin and epicatechin, both known for their antioxidant properties. These structural features grant flavonoids and flavanols the ability to donate electrons, neutralizing free radicals and reducing oxidative stress. Due to their abundance and variety in durian shells, these compounds contribute not only to the plant's defense mechanisms but also offer potential health benefits when utilized in human applications.

In terms of health benefits, flavonoids and flavanols are widely recognized for their antioxidant, anti-inflammatory, and cardiovascular protective effects [24]. Flavonoids are known to modulate cellular signalling pathways, which can reduce inflammation by downregulating the production of pro-inflammatory mediators such as cytokines [25]. This anti-inflammatory activity is crucial in managing conditions like arthritis and other chronic inflammatory diseases. Furthermore, flavonoids have shown potential in lowering blood pressure, improving lipid profiles, and enhancing endothelial function, which collectively contribute to cardiovascular health [26]. Flavanols, in particular, are noted for their positive impact on vascular health by promoting nitric oxide production, which improves blood flow and reduces the risk of atherosclerosis [27]. These compounds are also studied for their neuroprotective effects, as they may inhibit neuronal cell damage linked to neurodegenerative diseases such as Alzheimer's. Beyond human health, flavonoids and flavanols are used in the food industry for their natural antioxidant properties, which can extend the shelf life of products by preventing lipid oxidation. Additionally, in the cosmetics industry, these compounds are valued for their skin-protective qualities, offering anti-aging and anti-photoaging effects due to their capacity to neutralize free radicals [28] induced by UV exposure.

3.4.2 Quantitative methods

For the identification of flavonoids and flavanols in durian shells, several analytical methods are commonly employed. The aluminum chloride colorimetric assay is a straightforward method to measure total flavonoid content by forming a flavonoid-aluminum complex, which can be quantified spectrophotometrically. This method, while simple and effective for total flavonoid estimation, does not differentiate between specific flavonoids. The aluminum chloride colorimetric assay was used to determine the total flavonoid content (TFC) in various plant extracts. The flavonoid content was quantified by comparing the absorbance of samples to a calibration curve derived from a standard flavonoid, quercetin. TFC values in plant extracts ranged from 15 to 35 mg/g of dried weight, with certain samples showing higher levels depending on the type of plant material tested in the study by [29].

For a more detailed analysis, HPLC is frequently used, as it allows for the separation and quantification of individual flavonoids and flavanols. HPLC coupled with UV detection or mass spectrometry (MS) provides high sensitivity and specificity, making it a preferred method for profiling flavonoid composition. HPLC analysis revealed that durian fruit rinds are rich in flavonoids, achieving an optimal yield (82.17 mg QE g⁻¹ extract) under 60°C, 75% ethanol, and a 24-hour extraction [30]. The chloroform fraction (CHF) had the highest flavonoid (271.11 mg QE g⁻¹) and quercetin (1006.19 µg g⁻¹) content, along with notable antioxidant, enzyme inhibition, and cytotoxic activities. These findings suggest that CHF from durian rinds holds potential for pharmaceutical use.

3.5 Phenolic acids

3.5.1 Profile and applications

Durian shell is known to contain substantial amounts of phenolic acids, which are a class of bioactive compounds with numerous health-promoting properties. Phenolic acids are characterized by their aromatic ring structure bearing one or more hydroxyl groups, with a carboxylic acid functional group attached [31]. The two primary types of phenolic acids found in durian shells are hydroxybenzoic acids and hydroxycinnamic acids. The former includes compounds like gallic acid and p-coumaric acid, while the latter includes caffeic acid and ferulic acid. These compounds are notable for their antioxidant, anti-inflammatory, and antimicrobial activities, contributing to the overall health benefits associated with their consumption.

The health benefits of phenolic acids are broad and impactful. As potent antioxidants, phenolic acids help mitigate oxidative stress by scavenging free radicals, which is important for reducing the risk of chronic diseases such as heart disease, diabetes, and cancer [3]. Their anti-inflammatory effects are valuable in the

management of conditions like arthritis and inflammatory bowel disease. Additionally, phenolic acids have demonstrated antimicrobial properties, which make them effective against a wide range of bacterial and fungal infections, enhancing their value as natural preservatives in the food industry. These bioactive compounds also contribute to improved gut health by promoting the growth of beneficial gut microbiota.

In the food industry, phenolic acids extracted from plant materials, including durian shells, are increasingly used as natural antioxidants and preservatives, offering an alternative to synthetic additives. In the cosmetics industry, phenolic acids are incorporated into skincare products for their antioxidant and anti-aging effects, as well as their ability to combat environmental damage caused by UV radiation [3]. Moreover, phenolic acids are being explored for their potential in functional foods, given their health-promoting effects, particularly in terms of metabolic health.

3.5.2 Quantitative methods

The quantification of phenolic acids in durian shells can be achieved through various methods, including spectrophotometric and chromatographic techniques. One of the most widely used methods is the Folin-Ciocalteu assay, which involves the reduction of a phosphomolybdic-tungstic acid complex by phenolic compounds, leading to a color change that can be quantified spectrophotometrically. This method is simple and effective, but it may overestimate the phenolic content due to interference from other reducing compounds. Improvements of the Folin-Ciocalteu assay for more accurate phenolic content determination was also carried out by addressing interference from non-phenolic reducing agents [32]. The modified method calculates a corrected total phenolic content (TPC), which enhances specificity and reliability. This approach helps avoid overestimating phenolic acids due to reactions with substances like ascorbic acid, offering a more precise measure of plant phenolic content.

One of the most widely used methods is HPLC, which allows for the separation and quantification of individual phenolic acids based on their unique chemical properties. HPLC is highly accurate and provides detailed profiles of phenolic acids in plant materials, making it particularly valuable for studies involving durian shell source and more comprehensive analysis. HPLC was used to determine phenolic acids in walnut leaves, focusing on compounds like chlorogenic acid, caffeic acid, and ferulic acid. The method demonstrated high sensitivity with low limits of detection (LODs) and quantification (LOQs), achieving repeatability with relative.

IV. TOXICOLOGICAL CONCERNS, SAFETY ASSESSMENT, AND FUTURE PERSPECTIVES IN THE UTILISATION OF DURIAN SHELLS

4.1 Toxicological concerns and safety assessment

4.1.1 Potential toxins in durian shells

While durian shells hold considerable promise, it is essential to consider potential toxins that may pose risks to human health. Concerns surrounding heavy metals, pesticide residues, and natural toxins must be addressed to ensure the safe use of durian shells in consumer products [33]. Regular monitoring and assessment of these contaminants are crucial, especially given the agricultural practices in durian-producing regions. Regulatory perspectives on the safe use of durian shells must also be established, providing guidelines for safe levels of contaminants and ensuring that products derived from durian shells meet safety standards for consumer use.

4.1.2 Allergens and hypersensitivity

Another critical aspect of safety assessment involves the identification of allergens and hypersensitivity reactions related to durian or its components [34]. Some individuals may experience allergic reactions to durian, which can range from mild to severe. Investigating the potential for dermal or ingestion-related hypersensitivity is necessary to establish safety profiles for durian shell extracts. Understanding the immunological responses associated with durian exposure will contribute to the development of safer products and provide consumers with essential information regarding potential allergic reactions.

4.1.3 Environmental impact and bioaccumulation

The environmental impact of durian shell waste is also an important consideration, particularly concerning bioaccumulation of harmful substances [35]. Improper processing or disposal of durian shells could lead to environmental hazards, affecting soil and water quality. Analyzing the potential risks associated with the accumulation of toxins in the ecosystem is vital for sustainable waste management practices. Implementing strategies for responsible disposal and valorization of durian shells can mitigate environmental risks and promote a circular economy in the durian industry.

4.2 Future perspectives and research directions

Future research should focus on identifying and characterizing under-researched bioactive compounds present in durian shells. Exploring the full spectrum of bioactives could uncover new therapeutic applications in healthcare, particularly for conditions related to oxidative stress and inflammation. Investigating the synergistic effects of various compounds found in durian shells may also provide insights into their collective benefits, leading to the development of novel health products that capitalize on these natural ingredients [36].

The integration of durian shells into a circular economy model can enhance sustainability in food and agricultural industries [36]. By promoting the utilization of durian shells for various applications, including biofertilizers, animal feed, and health supplements, the industry can reduce waste and foster resource efficiency. Developing frameworks that facilitate the recycling and repurposing of durian shell waste will contribute to a more sustainable approach to agricultural practices and promote economic growth in durian-producing regions.

It is imperative to conduct thorough toxicological and clinical validation studies to advance the application of durian shell in health and industry [37]. Establishing safety profiles, evaluating the toxicity of bioactive compounds, and assessing their efficacy in human health will enhance consumer confidence and regulatory compliance. Future research should prioritize clinical trials to provide robust evidence for the health benefits associated with durian shell extracts, supporting their integration into mainstream healthcare and product formulations.

Emerging technologies in industrial applications present new opportunities for large-scale utilization of durian shell-derived materials [36]. Innovations in processing techniques, such as advanced extraction methods and material development, can maximize the potential of durian shells across various sectors, including food, cosmetics, and pharmaceuticals. Investing in research and development to explore these innovations will facilitate the growth of the durian industry, contributing to economic sustainability while promoting environmentally friendly practices

V. CONCLUSIONS AND RECOMMENDATIONS

Durian peel represents a valuable source of bioactive compounds with significant antioxidant, anti-inflammatory, and antimicrobial potential, offering promising applications across food, pharmaceutical, and agricultural industries. However, the presence of natural toxins such as cyanogenic glycosides, heavy metals, and oxalates restricts its use due to potential health risks. The detoxification strategies reviewed - thermal treatments, enzymatic degradation, fermentation, and solvent extraction - demonstrate the feasibility of reducing or eliminating these harmful compounds while preserving or enhancing the beneficial bioactive components. Continued research should focus on optimizing these detoxification processes to balance safety with efficacy, thereby unlocking the full potential of durian peel as a sustainable and functional resource. This approach will contribute to reducing agricultural waste while promoting innovative applications of durian peel in various sectors.

COMPETING INTERESTS

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

Phu H. Le conceived the idea, provided support, and critically revised the manuscript. Nghi B.P. Nguyen and Uyen P. Le structured the contents and wrote the manuscript. Phuc N.T. Le, Anh N. Nguyen, An D.X. Nguyen, and Duyen T.M. Nguyen contributed to the finding of materials and proofreading. All authors read and approved the final manuscript.

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