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Current status of conventional and green extraction methods for valuable compounds from shell waste of *Durio* spp. and other fleshy fruits: A review

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Abstract
The aim of this study was to review both conventional and green methods including their benefits and drawbacks for the extraction of valuable compounds from the shell waste of *Durio* spp. and other fleshy fruit, along with their possible industrial applications, especially pharmaceutical development. Durian has recently been considered as an exporting target for many Southeast Asian countries, with up to one million tons of production for the past 10 years. However, the developing industry of durian and many other fleshy fruits also put out a huge amount of shell as agricultural waste. This matter has posed a threat to both the environment and society. Addressing this issue involves implementing sustainable waste management practices, such as composting for industrial uses or extracting bioactive compounds for pharmaceutical applications. The methods used were reviewing and discussing literature during the past 15 years for the advantages and disadvantages of both conventional and green extraction techniques. Results highlighted the fact that several conventional ones are currently applied to recover bioactive compounds, e.g. Soxhlet extraction which rely on organic solvents but also pose great environmental and safety concerns. In response to these challenges, green technologies have emerged as eco-friendly alternatives, including: i) supercritical carbon dioxide extraction, which extract non-polar compounds without harmful residues; ii) pressurized liquid extraction, which enhances compound solubility using high pressure and temperature; iii) ultrasound-assisted extraction; and iv) microwave-assisted extraction, which employ sound waves and microwave energy to disrupt cell walls and improve extraction efficiency. And those methods not only provide solutions with various benefits regarding safety and cost for waste management but also offer new opportunities for developing high-value products in various industrial sectors. This study contributed crucial information on different extraction techniques and highlighted their crucial role in unlocking the potential of fruit shell bioactive compounds in pharmacology and beyond.

Keywords: *Durio* spp., bioactive compounds, extraction, shell waste

Introduction

Fruit shell waste is a growing environmental concern, especially in regions with high fruit consumption. On the one hand, large amounts of shells from fruits like durian, coconut, and mango are discarded as waste, contributing to landfill overflow and decomposition issues. These shells are often tough and fibrous, making them slow to break down naturally, which can lead to increased methane emissions which is responsible for global warming. Moreover, improper disposal of waste can lead to serious issues such as producing unpleasant odors and attracting pests like rats, flies, and cockroaches, which not only spread diseases but also worsen the sanitation problem. On the other hand, these fruit shells contain several bioactive compounds, e.g. antioxidants, flavonoids, polyphenols, and essential oils, which can be repurposed into value-added products [1]. Therefore, scientists are increasingly focusing on extracting those components from fruit shell waste, including durian (*Durio* spp.) and other fleshy fruits as part of a broader effort to find sustainable sources of valuable compounds. Traditional techniques such as solvent extraction and Soxhlet extraction are effective but often involve high solvent usage and long processing times. In recent years, green extraction technologies, e.g. supercritical carbon dioxide (CO_2) extraction, ultrasound-assisted extraction (UAE), and microwave-assisted extraction (MAE) have gained popularity due to their efficiency, reduced environmental impact, and ability to preserve thermolabile compounds. These methods offer rapid processing times, lower solvent consumption, and higher yields, making them more sustainable and attractive for large-scale applications [2].

Therefore, the purpose of this review was to explore and discuss different extraction techniques for bioactive components from durian shell and other fleshy fruit, especially the differences, advantages and disadvantage between conventional and green ones, as the focus on extracting bioactive compounds from fruit shells represents a major leap in sustainable resource utilization, transforming agricultural waste into valuable products. This trend not only lessens environmental impact but also offers immense potential for producing natural and functional compounds for various industries.

Shell waste issues of *durio* spp. and other fleshy fruits

Shell waste from *Durio* spp. and other fleshy fruits present significant environmental and waste management challenges. These fruits, especially durian, produce large amounts of inedible waste biomass, approximately 20,000 tons annually, including thick, spiky shells that are difficult to decompose and often being left and ended up in landfills and other inappropriate locations, e.g. roadside, residence areas, etc., that may pose certain negative impacts to the society. In reality, the shell waste from durian presents a significant environmental and waste management challenge, especially in regions where durian consumption is high, such as Southeast Asia [3]. Durian shells make up a large portion of the fruit's overall mass, contributing to substantial organic waste. For every durian harvested, approximately 50-70% of the total weight is inedible, consisting primarily of the thick, spiky outer shell, which is usually discarded as waste after the flesh is consumed. In addition, the sheer volume of waste from durians and similar fruits like jackfruit, coconut, and mango exacerbates the issue, as the shells are bulky and require space for disposal. In many fruit-producing regions, the accumulation of this organic waste leads to unpleasant odors, attracts pests, and can contribute to methane emissions if left to rot in landfills, further impacting climate change [4]. While progress is being made through research and innovation, particularly in countries like Thailand, Malaysia, and India, the issue remains critical, with ongoing efforts needed to promote sustainable waste management. Moreover, in Vietnam, research and applications reagarding ultilising of shell waste, especially in extracting for bioactives are still limited and underrated.

Valuable compositions of durian shell and their potential in a various industries

Despite their common negligence as a post-harvesting waste, shells of durian do contain significant amounts of valuable compositions, e.g. pectin: 73.67%, cellulose: 64%, hemicellulose: 30.7%, lignin: 15.60%, a large number of phytochemicals (5285.37 mg GAE.g^{-1} of polyphenols, 0.405 ± 0.002 mg QE.g^{-1} of flavonoids, and several saponins), and minerals (calcium, potassium, magnesium), etc., that recently attract huge attention as potential ingredients for applications in the food industry such as ingredients' substitutions thickening agent, natural preservatives, etc., and in the agricultural one such as biopesticides, biochars, adsorbent, paper-making materials, etc [1]. This trend leads to an increasing effort in utilization of durian shells.

Furthermore, several of those bioactive compounds are also extremely potential for pharmaceutical applications. Durian shell has long been exploited in Asian traditional medicine practices, including Vietnam due to its well-known therapeutic effects, e.g. relaxation, nourishing, internal heat control, etc. In addition, those bioactives are also proven recently in the development of modern medicinal practices for their antioxidant, anti-inflammatory, anti-microbial, anti-fungal, anti-cancer, anti-diabetic properties [5]. Therefore, the demand in effective extracting and recovering of those valuable agents is extremely high, leading to interests in finding and optimizing suitable extraction methods, especially those with both industrial capability and green status regarding environmental and social friendly [2].

Current status of extraction methods for valuable compounds from fruit shell waste and their potential

Extraction is the first step in isolating and purifying bioactive compounds from food sources. While some phenolic acids are water-soluble and can be extracted with ease, it can be more difficult to extract secondary metabolites that are insoluble, such as certain phenolic acids and flavonoids [6]. Traditionally, solvent extraction has been one of the most common methods used to recover bioactive compounds from fruit waste. This process typically involves the use of organic solvents like ethanol, methanol, or hexane to dissolve and extract target compounds. However, solvent extraction poses several environmental and safety concerns due to the potential toxicity of the solvents used, as well as the residual solvent traces in the final product. Other conventional methods, such as Soxhlet extraction, are time-consuming and require large volumes of solvent, making them less suitable for industrial-scale applications. It is understandable that innovative extraction techniques are attracting increased attention from researchers, as they require less time, use fewer solvents, and result in higher yields of bioactive compounds [2].

Fruits, especially those from tropical regions, are a diverse category from a botanical perspective. Currently, the industrial sector that produces the most residues generally is agriculture. Due to the increasing recognition of these fruits' nutritional and health-promoting qualities, their consumption is increasing in both national and international markets [7]. Despite these challenges, fruit shells are often underutilized, though they contain valuable bioactive compounds, fibers, and materials that could be used in sustainable industries, such as biofuel production, natural fiber composites, or pharmaceuticals. Bioactive compounds including antioxidants, polyphenols, and flavonoids extracted from fruit shells have anti-inflammatory, antimicrobial, and anticancer properties, making them suitable for pharmaceutical formulations. For instance, glycosides and triterpenoids extracted from durian shells have potential as anti-inflammatory agents, making them suitable for use in functional foods or medical applications [5]. Developing effective waste-to-resource strategies for durian shells and other fruit waste is essential to reduce the environmental burden and promote circular economy solutions.

Conventional extraction methods for valuable compounds from shell waste of *durio* spp. and other fleshy fruits

Conventional extraction methods refer to the traditional techniques used to isolate valuable compounds from raw materials. These methods are widely used in industries such as pharmaceuticals, food, cosmetics, and biofuels. These extraction methods for bioactive compounds from the shell waste of durian and other fleshy fruits generally involve mechanical, chemical, and thermal processes. Generally, these methods have been studied and applied for many years, making them well-understood and reliable. Moreover, industries are familiar with these processes, and there is abundant literature and experience in optimizing them. However, conventional extraction processes, such as solvent extraction or mechanical pressing, can result in low yields, meaning not all the valuable compounds are extracted from the raw material. Some conventional methods, such as maceration or Soxhlet extraction, can be slow and labor-intensive. In solvent extraction methods, it can be difficult to completely remove all solvent residues from the final product, which may affect the purity and safety of the extract [2].

1. Maceration

Maceration is a widely used conventional method for extracting bioactive compounds, particularly from plant materials, by soaking them in a solvent at room temperature. This low-tech method is simple, making it commonly be applied to various raw materials, including leaves, flowers, fruits, roots, and bark, to extract compounds such as alkaloids, flavonoids, tannins, and essential oils. It is crucial to choose suitable solvents due to dependence on the solubility of the desired bioactive compounds. In a study, methanol, ethyl acetate and dichloromethane were used as solvents to extract peanut hulls and palmyra palm peels, giving the extracts with good antioxidant activity. This research provides evidence of the potential use of fruit waste as the antioxidant source [8]. The extract from peels of orange, yellow lemon and banana by different solvents (methanol, ethanol, ethyl acetate) appeared to have antimicrobial activities [9].

Durian waste including durian shell, leaves and seed can be harnessed as a source of valuable compounds such as pectin and cellulose. Pectin was also extracted from durian peel using hydrochloric acid at pH 2.5, 85°C for 60 minutes [10]. Meanwhile, cellulose was extracted from durian rind using delignification with acidic sodium chlorite then followed by mercerization with 17.5% (w/v) sodium hydroxide [11]. The 70% ethanol extract from durian leaves appeared to have antidiabetic and antioxidant activities. [12]. Flavonoids were extracted by different solvents (ethanol, methanol, acetone, and hexane) then liquid-liquid extraction for fractionation from durian rind. The highest flavonoid content of 82.17mg QE/g extract was achieved when performing the extraction at 60°C using 75% ethanol and maceration time of 24 h [13].

2. Decoction

Decoction of fruit shells is a traditional method used to extract beneficial compounds from the shells of fruits by boiling them in water. This method can be applied to various fruit shells, such as those from pomegranate, durians, or dragon fruits, which are known for containing bioactive compounds like antioxidants, polyphenols, and fibers [14]. Decoction is an effective and simple way to utilize fruit shell waste, making it a sustainable practice for extracting nutrients and bioactive compounds. Decoction was employed to extract polysaccharides, anthocyanins, ellagitannins from the fresh mesocarp and exocarp of pomegranate peels [15]. In another study, the extraction process involves boiling the seeds of durian to release the polysaccharides, followed by filtration, and drying to obtain the gum [16].

3. Percolation

Percolation is a method of extraction that involves passing a solvent (usually water or alcohol) through a porous material, in this case, fruit shells, to extract bioactive compounds. This method is commonly used in pharmaceutical and natural product extraction processes and can be applied to fruit shells that contain valuable compounds like antioxidants, polyphenols, or pectin. Percolation is a relatively simple and efficient technique that allows for the continuous extraction of valuable compounds, making it a practical approach in industries focused on utilizing natural by-products like fruit shell waste [17].

Rakholiya *et al* (2011) conducted a study evaluating antioxidant potentials of different fruit peels by using different organic solvents including hexane, chloroform, acetone, and methanol. Fruit peel, in the form of dried powder, was extracted individually by cold percolation method and total polyphenol and flavonoids contents from the extracts were then determined and analyzed [18]. Percolation was also applied for durian husk extraction using pure methanol at a temperature of 30°C for 24 hours. The result showed that the total polyphenol content reached 250.39 mg acid gallic/g dry weight material [19].

4. Reflux extraction

Reflux extraction is a widely used method for extracting bioactive compounds from fruit peels, especially when higher extraction efficiency is desired. It involves the continuous boiling of a solvent and condensation of the vapor back into the extraction system, which allows for prolonged contact between the solvent and the material (fruit peel) to extract compounds thoroughly. The solvent is kept at its boiling point, ensuring that heat-sensitive compounds are not degraded. Reflux extraction requires a constant supply of heat, making it more energy-consuming compared to other extraction methods. Prolonged exposure to heat may degrade certain heat-sensitive compounds if not carefully controlled [17].

Reflux technique using 96% ethanol as the solvent was exploited to extract phytochemicals durian fruit peel. The extract was formulated to develop an effervescent tablet formulation, which is anticipated to serve as a convenient and accessible natural antioxidant option for the public [20].

5. Soxhlet extraction

Soxhlet extraction is a widely used technique for extracting compounds from solid materials. It was developed by the chemist Franz von Soxhlet in 1879, primarily for extracting lipids from solid samples. The process involves repeatedly washing the solid sample with a solvent, which is continuously evaporated and condensed, allowing for efficient and thorough extraction of the desired compounds. Soxhlet extraction is often used in research for isolating bioactive compounds, oils, and other natural products, providing a highly efficient method for exhaustive extraction. It is especially useful when the target compound is only slightly soluble in the solvent or present in low concentrations in the solid sample [21].

Using this technique, researchers indicated the presence of tannins and terpenoids, saponins, etc. in the orange peel extracted with different solvents hexane, methanol, acetone [22].Using the mixture of 80% ethanol and acetone as solvent also helped extract flavonoids from pomegranate peel. The extract from wild pomegranate peel exhibited the most potent inhibitory effect on the growth of all the tumor cell lines tested [23].

Besides, durian peel extract by using Soxhlet extraction with methanol as solvent appeared to have antibacterial activity, suggesting the new application of durian waste. It was used to formulate antibacterial bath soap, which then met the requirements for a stable physical-chemical evaluation including pH, foam height, and irritation [24].

Two grams of durian shell powder was the Soxhlet extraction method with 150 mL n-hexane for 8 hours. Then, the filtrate was evaporated and roasted at 105°C for 2 hours, cooled in a desiccator for 30 minutes, and weighed to an absolute weight [25].

Green extraction methods for valuable compounds from shell waste of *durio* spp. and other fleshy fruits

Green extraction technologies have emerged as more sustainable alternatives due to their high efficiency, little organic solvents, and short duration and energy requirements [26]**.** Numerous recent studies have focused on the comprehensive valorization of fruit waste to recover bioactive compounds using green extraction techniques.

1. Green solvent extracion

Unlike traditional solvents that may be toxic or harmful to the environment (like petroleum-based solvents), green solvents are typically non-toxic, biodegradable, and derived from renewable sources such as water and ethanol, which can help reduce the cost of equipment and operation. This technique, however, has its own limitations about extraction yield and duration. Aiming for sustainable development, it is also considered as a basic method to extract phytochemicals from the shell of fleshy fruits [27].

Using ethanol to extract durian peel, researchers have suggested the potentials of this waste as a source of bioactive compounds. Durian peel extract by ethanol could be considered as an active ingredient in hand sanitizer since it has antibacterial activity. In an antiseptic test, the sample showed the ability of reducing the growth of *Escherichia coli* and *Salmonella typhosa*, and gram-positive bacteria, *Staphylococcus aureus* [28]. The extract was also reported to have the ability of preventing dental caries since it is antibacterial against *Streptococcus mutans* and *Enterococcus faecalis* [29, 30].

Durian peel extract by 95% ethanol was analyzed to determine antioxidant activity and anti-inflammatory [31]. Another study optimized extraction conditions for flavonoids extracted from durian fruit rinds and evaluated the biological activities of the flavonoid-rich extracts. The maximum flavonoid content, 82.17 mg QE/g extract, was obtained by extracting at 60°C with 75% ethanol in 24 hours [13].

2. Supercritical fluid extraction

Supercritical CO_2 is used to extract lipophilic compounds (like essential oils or fatty acids) from fruit shells. This method is more efficient and environmentally sustainable, as it produces high-purity extracts without harmful solvents. Nevertheless, the equipment for supercritical CO2 extraction is expensive to purchase and set up. The process also requires high pressures (up to 10,000 psi), which adds to the cost due to the need for specialized pumps and pressure vessels. Therefore, this method is commonly applied in laboratories, making it rarely used in industry [17].

Researchers have conducted various experiments extracting valuable compounds like antioxidants, essential oils, flavonoids, and polyphenols from fruit shells. Fiber oil was extracted from palm-pressed mesocarp fiber by supercritical carbon dioxide extraction at 40°C. This technique has been demonstrated for selective concentration of palm minor components, especially to separate vitamin E and squalene from carotene [32]. The extract from a mixture of pomegranate peels and seeds achieved the highest yield (11.5%) at 40 MPa and 40°C [33].

3. Pressurized liquid extraction

Pressurized liquid extraction, also known as accelerated solvent extraction, is a technique used to extract bioactive compounds from solid and semi-solid materials using solvents under high pressure and elevated temperature. This method is particularly efficient in reducing the amount of solvent used and extraction time, while enhancing the yield of target compounds compared to conventional methods like Soxhlet extraction. In some cases, pressure is applied to physically extract oils or other liquids from shell waste, such as in the case of fruit peels [34].

Barrales *et al* (2018) extracted phenolic compounds from orange peel [35]. This compound was also isolated by in-line coupling pressurized liquid extraction and solid-phase extraction from lemon peel [36]. Bioactive compounds from pomegranate peel was a source of bioactive compounds extracted by using a combination of pressurized water and ethanol [37].

4. Liquid-liquid extraction

Liquid-liquid extraction (LLE), also known as solvent extraction, is a separation process used to isolate specific compounds from a liquid mixture by transferring them into another immiscible liquid, typically an organic solvent. The technique relies on the differing solubilities of compounds in two immiscible liquids, usually water (or an aqueous phase) and an organic solvent [17].

This technique was applied in preparing pomegranate peel extract which is rich in ellagic acid. Partitioning of the 10% v/v water in methanol extract of pomegranate peel between ethyl acetate and 2% aqueous acetic acid gives the result with increment in ellagic acid content from7.06% to 13.63% w/w [38].

5. Microwave-assisted extraction

This method utilizes microwave energy to heat solvents in contact with a sample, enhancing the efficiency of extracting target compounds. The microwaves cause rapid heating of the solvent and sample, which increases the penetration of the solvent into the sample matrix and speeds up the extraction process.

Scientists used this technique to extract soluble phenolic compounds of rambutan peels [39], pectin from orange peel [40]. Essential oil from orange peel could be collected by placing orange peels in the microwave reactor, without any added solvent or water. The internal heating of water present within the orange peels causes the oil glands and sacs to expand, leading to the rupture of the glands and oil-containing receptacles, liberating essential oil [41].

6. Ultrasonic-assisted extraction

Ultrasonic-assisted extraction is a technique used to extract bioactive compounds from fruit peels and other materials using high-frequency sound waves. The ultrasonic waves generate cavitation bubbles in the solvent, which collapse and produce intense shear forces. These forces break down the plant cell walls, and therefore, enhance the release of target compounds into the solvent, making the extraction process faster and more efficient.

The method helped extract pectin from grapefruit peel [42], and pectin from mango peel [43]. Whereas, phenolic from pomegranate peel can be extracted by pulsed ultrasound-assisted extraction [15] or by ultrasonication maceration-assisted extraction method [44]. Bioactive compounds from dragon fruit peel (dry weight) were also extracted using ultrasound [45]. Moreover, a 1: 9 ratio of durian peel to ethanol extraction using ultrasonic assisted extraction in 20 minutes gave the highest extraction yield of 12.77 ± 0.16%, antioxidant activity (IC50) of 38.33 ± 0.12 ppm, total phenolic content of 63.30 ± 0.08 mg GAE.g^{-1} and total flavonoids content of 47.53 ± 0.48 mg QE.g^{-1} [46].

7. Enzyme-assisted extraction

This method is commonly applied to tough materials like fruit shells or seeds, where the cell walls are dense and difficult to break down using conventional methods. For example, it can be used to extract bioactive compounds from the shells of fruits like coconut, pomegranate, or durian. Specific enzymes, such as cellulases, pectinases, and proteases, are selected depending on the composition of the fruit shell. It is often more selective and environmentally friendly compared to chemical methods. This method is usually combined with others to achieve high efficiency [47]. Optimized enzyme-assisted supercritical fluid extraction from pomegranate peel not only enhanced the recovery of extractable bioactive components; nevertheless, the levels of extracted total phenolics and antioxidant activities in terms of determination of radical scavengers, inhibition of linoleic peroxidation, and trolox equivalent antioxidant capacity were also significantly improved [48]. Using ViscozymeL and microwave treatment could help achieve high phenolic content and antioxidant activity from pomegranate peel [49]. Enzyme treatment showed to have the ability of modifying physical properties, which helps break plant cell walls and release more phytochemicals. Of all enzymes used, pectinase was the most effective in hydrolyzing polysaccharides in durian rinds than was cellulase or amylase [50].

Conclusion

The issue of fruit shell waste is growing as the demand for processed fruits increases, leading to significant amounts of discarded shells, peels, and rinds. However, the bioactive compounds obtained from shell waste exhibit numerous pharmacological properties, including antioxidant, anti-inflammatory, antimicrobial, and anticancer properties, with potential applications, e.g. drug development, nutraceuticals, and natural health supplements. In the pharmaceutical industry, antioxidants and polyphenols can be used in the development of drugs and supplements to combat oxidative stress and inflammation. In the cosmetic industry, these bioactive compounds serve as natural ingredients in anti-aging and skin-care products. Furthermore, the extracted compounds have applications in the food industry as natural preservatives or functional ingredients. As the global demand for sustainable and eco-friendly processes grows, the use of green extraction technologies to recover valuable compounds from fruit shell waste will likely increase in replacement for conventional ones. These methods not only provide a solution for waste management but also offer new opportunities for developing high-value products in various industrial 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. Phuc N.T. Le structured the contents. Phuc N.T. Le and Anh N. Nguyen wrote the manuscript. An D.X. Nguyen and Uyen P. Le contributed to the finding of materials and proofreading. All authors read and approved the final manuscript.

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