Application of Conventional and Non-Conventional Extraction Methods to Obtain Functional Ingredients from Jackfruit (Artocarpus heterophyllus Lam.) Tissues and By-Products

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Abstract: In recent years, researchers in the pharmaceutical and food areas focused on finding the best ways to take advantage of functional ingredients present in jackfruit tissues and by-products such as phenolics and pectin. Many of these studies focused on adding value to the by-products and decreasing their negative environmental impact. However, the type, quantity, and characteristics of jackfruit functional ingredients are highly dependent on the extraction method, either through conventional or non-conventional technologies, and the jackfruit tissue used, with peel and seeds being the most studied. The reported studies suggest that extractions and pre-treatments with emerging technologies such as ultrasounds, microwaves, radio frequency, or supercritical fluids can facilitate the release of functional ingredients of jackfruit; reduce the time and energy consumption required; and, in some cases, improve extraction yields. Therefore, emerging technologies could increase the functional potential of jackfruit and its by-products, with promising applications in the pharmaceutical and nutraceutical industries.

Keywords: jackfruit; jackfruit processing; by-products; extraction methods; phenolic compounds; pectin; emerging technologies; innovative technologies; functional ingredients; bioactive compounds

1. Introduction

The tropical fruit known as Jackfruit (Artocarpus heterophyllus Lam.) is native to Thailand, India, and Indonesia, and it is also found in other Asian countries, northern Australia, parts of Africa [1], and Latin America. Jackfruit trees belong to the Moraceae family [2]. They are medium-sized, characterized by reaching between 8.5 m to 24 m in height, and their fruit is born from its main and lateral branches [3]. Fruits can weigh up to 45 kg and measure up to a length of 91 cm and a diameter of 51 cm [4]. Ranasinghe et al. [5] described the outer part of the jackfruit shell (commonly known as rind or peel) to have conical carpel apices that cover a thick rubbery wall (Figure 1A). Inside the fruit, a non-edible core forms a longitudinal axis that is fused with the rags, which in turn are connected to the rind of the syncarp (Figure 1B) [5]. The bulbs are the fleshy edible region found between the rags (Figure 1B); each one is comprised by the pulp surrounding a seed (Figure 1C) [5]. Jackfruit seeds (Figure 1D), which vary in number between 100 and 500, represent 18–25% of the fruit’s total weight [1]. The kernels of the seeds represent 90–95% of their weight; on the other hand, the pulp represents 30% of the fruit weight [1]. According to Akter & Haque [6], around 70 and 80% of the jackfruit components are non-edible; from them, about 60% correspond to the outer rind, perianth, and central core and are considered waste and usually discarded.
One of the jackfruit’s main attributes is its high nutritional content. In a review article, Swami et al. [3] presented data from Samaddar regarding the composition of 100 g of ripe jackfruit pulp with a caloric content of 84. The results are as follows: 77% moisture, 18.9% of carbohydrates, 1.9% protein, 1.1% fiber, 0.8% total minerals (30 mg phosphorus, 20 mg calcium, 500 mg iron), 0.1% fat, 30 mg thiamine, and 540 UI vitamin A [3]. In addition to the nutritional content, jackfruit has specific bioactive compounds, which demonstrated positive effects in helping prevent certain chronic diseases, including cancer, cardiovascular diseases, and diseases related to aging [7]. For this reason, jackfruit is considered a medicinal plant in some countries [8].

The most reported bioactive compounds in jackfruit are phenolic compounds [1] and carotenoids [3]. However, there is evidence of other functional ingredients such as prebiotics including indigestible polysaccharides and oligosaccharides [9,10]; pectin [11]; minerals such as Ca, Fe, K, Mg, and Na [12]; essential fatty acids (EFAs) such as alpha-linoleic and linoleic [13]; and other fatty acids such as palmitic, oleic, stearic, myristic, lauric, capric, and arachidic acids [14], among others. Jackfruit functional ingredients are of great interest owing to their possible applications in the food and pharmaceutical industries, specifically for their health-related benefits. However, these components are not necessarily present in a high amount in jackfruit [15]. For those reasons, there has been an increasing interest in finding strategies for their extraction, especially those focusing on using innovative and emerging technologies.

Various studies in the literature showed the effect of conventional and non-conventional extraction methods to obtain jackfruit functional ingredients; among the non-conventional methods, some use emerging technologies to extract or as a pre-treatment. Among the studies using conventional extraction, applying solvents such as methanol [16] and oxalic acid [17] stands out, as well as the extraction with hot water [18]. Regarding extraction by emerging technologies, radio frequency-assisted [19] and supercritical fluid (SFE) with CO$_2$ [20] extractions have attracted attention owing to their less negative impact on the environment and safety of the final product obtained in comparison with other methods using non-conventional technologies. Regardless of the extraction method, the yields of a particular functional compound will vary depending on the jackfruit tissue utilized.
for the extraction; the most common selected tissues for this process are peel and seeds, by-products generated from the fruit consumption.

The limited utilization of pericarp and other inedible parts of the jackfruit makes them a source of contamination [21]. Agro-industrial by-products such as peels, seeds, and residual fruit pulp can be a good natural source of antioxidants such as phenolic compounds [22]. Antioxidants include bioactive compounds capable of counteracting the damage of oxidation processes in the body by assisting chemical reactions [23]. Hence, applying emerging technologies in new processes to transform the jackfruit by-products is useful to obtain functional ingredients or components and may help stop the negative impact on the environment.

The purpose of this publication is to review the following: (1) the most relevant functional ingredients in the jackfruit tissues and by-products; (2) the impact of conventional extraction and assisted extraction by emerging technologies in the functional ingredient yield; and, finally, (3) the functionality and applications of those functional ingredients.

2. Bioactive Compounds of Jackfruit

This study will focus on the species of jackfruit *Artocarpus heterophyllus* Lam., the one with the most information reported. Furthermore, information on the other jackfruit species is scarce.

2.1. Pulp

Jackfruit pulp, the edible part of the fruit, has several functional ingredients and bioactive compounds. One of its most notable properties is its vitamin C content, with a reported value of 8.16 mg/100 g [24]. On the other hand, phenolic acids, flavonoids, flavanones, and their derivatives were found in extracts of dietary fiber from jackfruit pulp when characterizing their composition by chromatographic analysis and a quadrupole time-of-flight mass spectrometer in negative ion mode used for detection (UPLC-ESI-QTOF-MS/MS) [25]. Additionally, Singh et al. [26] reported the presence of three phenolic acids in the unripe pulp extracts, gallic (9.70 µg/g), ferulic (8.04 µg/g), and tannic (4.87 µg/g) acids, when analyzed by high-performance liquid chromatography (HPLC). These values differed from those obtained from the ripe pulp, where the amount of gallic acid was almost double (19.31 µg/g), the ferulic acid decreased (2.66 µg/g), while the tannic acid slightly increased (5.24 µg/g) [26]. Moreover, Galvez & Dizon [27] reported values for the fresh pulp’s total phenolic content between 125.91 and 127.73 mg CE (catechin equivalent)/100 g. In contrast, the tannin content was found to be between 127.73 and 208.72 mg VE (vanillin equivalent)/100 g depending on the physical, chemical, and functional properties [27]. Regarding the carotenoid presence in the pulp, de Faria et al. [28] found five major types of carotenoids, including 24–44% all-trans-lutein, 24–30% all-trans-β-carotene, 4–19% all-trans-neoxanthin, 4–9% 9-cis-neoxanthin, and 4–10% 9-cis-violaxanthin using high-performance liquid chromatography coupled with photodiode array and mass spectrometry detectors (HPLC-PDA-MS/MS). Their study showed a maximum total value of carotenoids of 150.3 µg/100 g [28].

Regarding fatty acids, Chowdhury et al. [14] reported a total amount of fatty acids of 31.9 mg per 100 g of petroleum ether extract (105 mg per 100 g of whole fruit) in the edible part (fertilized fleshy perianths) of jackfruit.

2.2. Seed

Jackfruit seeds have many bioactive compounds such as polyphenols, and within these, mainly phenolic acids, flavonoids, and stilbenes [29]. Depending on the extraction technique used, those compounds might present variations in their chemical composition or bioactivity [20]. Kumoro et al. [1] reported values for polyphenols (243 ± 27.0 mg of gallic acid equivalent (GAE)/100 g dry seeds), flavonoids (2.03 ± 0.06 mg EC/100 g dry seeds), tannins (0.06–0.229 mg/100 g of seed), ferulic acid (0.216 mg/100 g of seed), and gallic acid (1.105 ± 0.12 mg/100 g of seed).
Some studies reported the oils present in jackfruit seeds. The main fatty acids present are linoleic and linolenic acid [1]. Nagala et al. [30] evaluated the oils’ fatty acids composition and antioxidant potential in five different jackfruit species. Their study found jackfruit to be a good source of essential fatty acids (EFAs) with a notable antioxidant activity; higher percentages were observed in the DPPH test for *Artocarpus integer* (98.4 ± 0.2% of inhibition/50 µL), followed by *Artocarpus integrifolia* (98.2 ± 0.3% of inhibition/50 µL) and *Artocarpus heterophyllus* (87.4 ± 0.2% of inhibition/50 µL). Additionally, the seeds are good sources of minerals, such as potassium, which has the highest concentration (2470 ppm), followed by calcium, magnesium, and sodium; the seed’s kernel contains 148.50 ppm of iron [1]. Jackfruit seeds also contain 400 mg/g extract of non-reducing sugar, a potential prebiotic ingredient [10].

There are reports that seed powder nanoparticles showed antimicrobial activity against *Escherichia coli* and *Bacillus megaterium* [3]. The jackfruit seed crude extracts contain ja-calin protein [31]. Regarding the antioxidant activity of peptides from jackfruit seeds, Chai et al. [32] found, by subjecting proteins to trypsin digestion, that the peptide JFS-2 has antioxidant activity, which can be affected by pH, temperature, and gastrointestinal digestion.

2.3. Peel

Approximately half of the ripe jackfruit corresponds to the outer peel [33], a sizeable unused portion of fruit because it is not edible. The peel is rich in calcium [33]. It also contains between 8.94 and 15.14% of pectin in dry matter (DM) [34], making it an important source of this polysaccharide [21]. Pectin is an acid hetero-polysaccharide present in the cell walls and middle lamellae of plants grown in the soil [35]. It consists of α-1,4-linked D-galacturonic acid partially esterified with methyl groups and several neutral sugars, such as L-rhamnose, L-arabinose, and D-galactose [17].

According to Zhang et al. [16], jackfruit peel extracts have a higher total phenolic content and total flavonoids than extracts from pulp, seeds, and flakes. These authors reported 48.04 mg GAE/g DM and 2.79 mg of quercetin equivalents (QE)/g DM, respectively [16]. Sharma et al. [36] reported that the jackfruit shell is a potential source of β-carotene, ascorbic acid, and polyphenols such as catechin and chlorogenic acid; the amounts found of phenolic and flavonoids were 158 ± 0.34 mg GAE and 10.0 ± 0.64 mg CE, respectively. Finally, Chowdhury et al. [14] reported a total amount of fatty acids of 34.3 mg/100 g of petroleum ether extract (12.6 mg/100 g of whole fruit) in the outer rind of jackfruit.

3. Methods Used in the Extraction of Functional Ingredients from Jackfruit

Conventional technologies used to extract functional ingredients from food generally consist of liquid–liquid or solid–liquid extraction [37]. These techniques are efficient in yield, but present some challenges regarding the general cost of the method and the safety of the final product [38]. Consequently, modification and development of the techniques have occurred, including adding pre-treatment steps to help release the compounds from the matrix [37]; this is where emerging technologies come into play. Emerging or modern technologies sometimes overcome the challenges from conventional technologies such as high energy consumption; food product matrix overheating; and loss of stability, functionality, or safety of the final product [38]. Finally, both conventional and emerging technologies have advantages and disadvantages in terms of cost and safety of the final product; however, emerging technologies provide better quality products and reduce the impact on the environment [39]. A summary of the most widely used extraction methods for functional ingredients present in jackfruit is presented in Figure 2.
Figure 2. Conventional and non-conventional extraction methods and conventional extraction assisted by non-conventional technologies for functional ingredients from jackfruit tissues and by-products.

3.1. Conventional Technologies

Research performed using conventional technologies to extract jackfruit functional ingredients focused on phenolic compounds, pectin, jacalin, and prebiotics. The majority of the studies in the literature utilized jackfruit by-products instead of the edible part, mostly to give them added value and reduce their environmental impact [40]. Additionally, this approach allows using all parts of the fruit, which means a lower economic cost to obtain the matrix or raw material for the extraction [17]. Table 1 presents some of the reported works comparing the yields obtained from different extraction methods, solvents, and processing conditions.

When comparing reported yields of non-extractable polyphenol (NEPP) extraction processes through alkaline, acidic, or enzymatic hydrolysis from the dietary fiber of jackfruit pulp, those extracted from alkaline hydrolysis had the highest content (64.9 mg GAE/10 g DM) and antioxidant properties, having an ABTS+ elimination capacity nine times greater than the acid extract and four times greater than the enzymatic extract [25]. Islam et al. [40] compared the yields of polyphenol content obtained from pressurized hot-water extraction (PHWE), enzyme-assisted extraction (EnE), and organic solvent extraction (OSE) systems using the peel, seeds, and rags of jackfruit. They observed higher yields using the combination PHWE and peel by obtaining 47.22 ± 2.31 (mg GAE/g DM) [40]. Besides, the PHWE of polyphenols from jackfruit seeds was reported by Shakhthi Deve et al. [18], in which jackfruit obtained the highest yield (87.52%) compared with other fruits such as sweet orange (Citrus sinensis) (74.79%) of antiglycation activity, concluding that flavonoid compounds like rutin, quercetin, and quercetin-3-O-xiloside could be responsible for that. Another study compared the effect of maceration (MAC) and Soxhlet (SOX) extraction techniques with ethanol and hexane on the composition and biological activity of the corresponding extracts [20]. Their results from extracts of jackfruit seeds showed that the best antioxidant activity and recovery yields correspond to SOX extraction with ethanol (12.08 ± 2.13 mg GAE/g) compared with the 1.89 ± 0.01 mg GAE/g recovered by MAC with ethanol [20]. Subcritical water-assisted extraction (SCWE) is another method that has been used to extract compounds from jackfruit, which Li et al. [21] compared based on...
pectin yields with a citric acid extraction method. Despite SCWE having a lower yield, 149.6 g/kg (14.96%) against 16.83% from the citric acid method, it showed a reduction in extraction time and energy consumption when operating at 138 °C for 9.15 min and a ratio of 17.03 mL/g liquid/solid (L/S) [21].

Furthermore, Shanooba et al. [29] tested the combination of different solid–solvent ratios, solvent concentrations, and times to extract polyphenols from jackfruit seeds through the conventional solvent extraction (CSE) method. They concluded that the best extraction performance was with 95% ethanol for 30 min at a solvent ratio of 2.5:25 g of jackfruit seed powder/mL of ethanol [29]. Likewise, Zhang et al. [16] reported that, when using 90% methanol for 6 h to extract phenolics, jackfruit peel yields were 4.95, 4.65, and 4.12 times higher than other parts of the fruit such as seeds, pulp, and flake, respectively. However, when comparing the phenolic content obtained from the peel to that from the fiber or core, the one from the fiber is higher (23.28 ± 4.73 mg/g), followed by the peel (17.07 ± 5.16 mg/g), and finally the core (15.68 ± 3.74 mg/g), using a CSE with methanol as solvent followed by 48 h incubation [12].

Sundarraj et al. [17] conducted experiments to determine the best temperature and time conditions for pectin extraction with oxalic acid from jackfruit peel, where they found that the best performance results corresponded to 90 °C and 60 min. Meanwhile Bhornsmithikun et al. [10] studied the effects of temperature, extraction times, and liquid–solid ratios’ variations for the extraction of prebiotics, finding that a 50% ethanol extraction for 15 min at 60 °C at a ratio of 10:1 (v/w) had the best yields of non-reducing sugar content. More recently, Mohamad et al. [31] reported the extraction of jacalin from jackfruit peel using a sodium bis (2-ethylhexyl) sulfosuccinate/isoctane reverse micellar system.

3.2. Emerging Technologies

Some studies on the extraction of functional ingredients present in jackfruit have applied emerging technologies to assist in the process, such as ultrasounds, microwaves, and radio frequency, as a combined treatment or as a pre-treatment to the samples to facilitate further extraction. The results varied according to the technology used, the matrix, and the compounds of interest extracted, as shown in Table 2. Among those studied, some resulted in higher performance than conventional methods alone when using techniques including ultrasonic-microwave assisted extraction (UMAE) and ultrasound-assisted extraction (UAE) [5]. The implementation of emerging technologies to extract functional ingredients from jackfruit has not been fully explored, which presents a window of opportunity for new research.

Few extraction methodologies for jackfruit pulp compounds reported in the literature use non-conventional technologies compared with those for seeds and peel. One of those is a study by Singh et al. [26], who used UAE (15 min at 4 °C) with ethanol as a solvent to recover phenolic acids from ripe and unripe jackfruit pulp. This study concluded that jackfruit has a good content of phenolic acids in its raw and ripe edible parts, with 19.31 ± 1.8 μg/g of gallic acid being the maximum detected amount in raw fruit pulp [26].
Table 1. Conventional extraction of functional ingredients from jackfruit parts.

| Part   | Technique                          | Extraction Conditions                                                                 | Functional Ingredients and Yields                                                                 | Ref.                  |
|--------|------------------------------------|----------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|-----------------------|
| Pulp   | Alkaline hydrolysis                | 2.00 g of sample mixed with 8.00 mol/L of NaOH, liquid–solid ratio of 20 mL/g, and extraction time of 4 h. | Non-extractable polyphenols 64.90 mg GAE/10 g DM                                                 | [25]                  |
| Acid hydrolysis | 2.00 g of sample mixed with 9.00% of H\textsubscript{2}SO\textsubscript{4}, liquid–solid ratio of 20 mL/mg, and extraction time of 4 h. | Non-extractable polyphenols 21.80 mg GAE/10 g DM                                                 |                      |
| Enzymatic hydrolysis | 2.00 g of sample mixed with 2.40 mg/mL of cellulase and pectinase at mass ratio 2:1, liquid–solid ratio of 20 mL/g, and extraction time of 90 min. | Non-extractable polyphenols 25.00 mg GAE/10 g DM                                                 |                      |
| Seed   | Conventional solvent (1)           | Phenolics were extracted with a solid–solvent ratio of 2.50:25.00 g/mL at 30 min in 95.00% ethanol concentration. | (1) Total phenolic content: 122.17 ± 0.41 µg GAE/mL Total flavonoid content: 0.47 ± 0.02 mg CE/mL Condensed tannin: 0.34 ± 0.08 mg CE/mL | [29]                  |
|        | Phenolics were extracted at 60 °C, extraction time of 15 min, and L/S ratio at 10:1(v/w) using 50.00% ethanol as a solvent. | (2) Prebiotics were extracted at 60 °C, extraction time of 15 min, and L/S ratio at 10:1(v/w) using 50.00% ethanol as a solvent. | Jacalin yield: 88.04 ± 1.30% Average non-reducing sugar: 400 mg/g extract | [10]                  |
| Reverse micellar extraction | Sodium bis(2-ethylhexyl) sulfosuccinate (AOT)-based reverse micellar system. Aqueous phase pH 4.58, 125.00 mM NaCl and 40.00 mM AOT, 300 rpm for 20 min at room temperature. |                                                   | [31]                  |
| Enzymes | Phenolics were extracted by dissolving 2.50 g of dry powder sample in 50 mL of 0.10 M phosphate buffer (pH 4.00) according to a solid/liquid ratio of 1:20 (g/mL) and adding an aqueous enzyme solution (Viscozyme® L). | Total phenolic content: 10.54 ± 1.41 mg GAE/g DM Total flavonoid content: 0.19 ± 0.03 mg QE/g DM | [40]                  |
| Hot water | Phenolics were extracted by weighing out 0.50 g of powdered material and extract with 25 mL of distilled water by placing it in a boiling water bath at a temperature of 90 °C for 5 min. | Total phenolic content: 41.65 ± 13.95% | [18]                  |
| Pressurized hot water | Phenolics were extracted by mixing 10.00 g of dry powder samples with 200 mL of distilled water in a 1000 mL pressure cooker according to a solid/liquid ratio of 1:20 (g/mL). | Total phenolic content: 7.02 ± 0.39 mg GAE/g DM Total flavonoid content: 0.48 ± 0.13 mg QE/g DM | [40]                  |
| Maceration | Phenolics were extracted by placing 50.00 g of sample in 200 mL of ethanol for 196 h with daily manual stirring at room temperature (25 °C). | Total phenolic content: 1.89 ± 0.09 mg GAE/g | [20]                  |
| Soxhlet | Recycle 150 mL of ethanol over 5.00 g of sample in a Soxhlet apparatus for 6 h. | Total phenolic content: 12.075 ± 2.131 mg GAE/g | [20]                  |
| Peel   | Conventional solvent (1)           | Phenolics were extracted by dispersing 2.00 g of samples in 60 mL of 90.00% methanol at a solid/liquid ratio of 1:30 (g/mL) and extracted at room temperature for 6 h in a shaker at 100 rpm. | Phenolics | [16]                  |
|        | Phenolics were extracted with methanol following a 48 h incubation at 24 °C. | (1) Total phenolic content: 48.04 mg GAE/g DM Total flavonoid content: 2.79 mg QE/g DM |                      |
|        | Phenolics were extracted with oxalic acid, 90 °C and 60 min. | (2) Phenolics: 17.07 ± 5.16 mg/g Total flavonoid content: 28.55 ± 12.42 mg/g | [12]                  |
|        | Pressurized hot water              | Phenolics were extracted by mixing 10.00 g of dry powder samples with 200 mL of distilled water in a 1000 mL pressure cooker according to a solid/liquid ratio of 1:20 (g/mL). | Total phenolic content: 14.19 ± 0.85 mg GAE/g DM Total flavonoid content: 1.25 ± 0.07 mg QE/g DM | [40]                  |
|        | Phenolics were extracted with oxalic acid, 90 °C and 60 min. | (3) Pectin: 39.05 ± 0.59 g/g of pectin Total flavonoid content: 39.05 ± 0.59 g/g of pectin |                      |
|        | Extraction assisted with subcritical water | | |                      |
|        | Extraction temperature 138 °C, extraction time 9.15 min, L/S ratio 17.03 mL/g. | Total phenolic content: 11.52 ± 0.81 mg QE/g DM Total flavonoid content: 14.72 ± 2.31 mg QE/g DM | [21]                  |
|        | Phenolics were extracted by dissolving 2.50 g of dry powder sample in 50 mL of 0.10 M phosphate buffer (pH 4) according to a solid/liquid ratio of 1:20 (g/mL) and adding an aqueous enzyme solution (Viscozyme® L). | Total phenolic content: 14.19 ± 0.85 mg GAE/g DM Total flavonoid content: 1.25 ± 0.07 mg QE/g DM | [40]                  |

DM: dry matter, GAE: gallic acid equivalent, QE: quercetin equivalents, CE: catechin equivalent.
Table 2. Emerging technologies of assisted extraction of functional ingredients from jackfruit parts.

| Parts   | Technique                          | Extraction Conditions                                                                 | Functional Ingredients and Yields                     | Ref. |
|---------|------------------------------------|---------------------------------------------------------------------------------------|-------------------------------------------------------|------|
| Pulp    | Ultrasound-assisted extraction     | 1.00 g of sample finely crushed with 5–10 mL of ethanol water (80–20; v/v), ultrasonicated (15 min at 40 °C) and centrifuged (15 min at 7500 rpm). | Phenolic acids                                       | [26] |
|         |                                    |                                                                                       | Raw pulp                                              |      |
|         |                                    |                                                                                        | Gallic acid: 9.70 µg/g                                |      |
|         |                                    |                                                                                        | Ferulic acid: 8.04 µg/g                               |      |
|         |                                    |                                                                                        | Tannic acid: 4.87 µg/g                                |      |
|         |                                    |                                                                                        | Ripe pulp                                             |      |
|         |                                    |                                                                                        | Gallic acid: 19.31 µg/g                               |      |
|         |                                    |                                                                                        | Ferulic acid: 2.66 µg/g                               |      |
|         |                                    |                                                                                        | Tannic acid: 5.24 µg/g                                |      |
| Seed    | Ultrasound-assisted extraction     | 7.00 g of sample in 210 mL of solvent (ethanol) and mix. Ultrasound equipment with a probe is used for 4 min at 70% power (maximum power-500 W) and a frequency of 20 kHz. | Total phenolic content:                                | [20] |
|         | Microwave-assisted extraction      | Immerse 1.00 g of the powdered sample in 100 mL of ethanol using an ETHOS-Milestone extractor, 5 min extraction time, 450 W microwave power, and 50 °C of extraction temperature. | Phenolic compounds yield:                             | [41] |
|         | Supercritical fluid extraction with CO2 | 7.00 g of sample is placed into a column (127.5 mm length × 10 mm diameter and internal volume of 10 cm³) to form the bed of fixed particles. Conditions: temperature of 50 °C, pressure of 12 MPa, CO2 flow rate of 4.0 mL min⁻¹, and extraction time of 150 min. | Total phenolic content:                                | [20] |
|         |                                    |                                                                                        | 0.841 ± 0.067 mg GAE/g                                |      |
|         |                                    |                                                                                        | 17.34 mg/g%                                           |      |
|         |                                    |                                                                                        | 0.937 ± 0.004 mg GAE/g                                |      |
| Peel    | Radio frequency-assisted extraction| Radio frequency time of 61.50 min, the ratio of liquid to solid 20.63:1 mL/g, and pH 2.61. | Pectin yield:                                         | [19] |
|         | Ultrasonic microwave-assisted extraction | Ultrasound time: 29 min, microwave time: 10 min, power 50 of W, 86 °C, and solid to liquid ratio of 1:48 g/mL. | 29.40%                                               |      |
|         | Ultrasound-assisted extraction     | Liquid–solid ratio of 15:1 mL/g, pH of 1.60, sonication time of 24 min, and temperature of 60 °C. | Pectin yield:                                         | [34] |
|         |                                    |                                                                                        | 21.50%                                               |      |
|         |                                    |                                                                                        | 14.50%                                               |      |

GAE: gallic acid equivalent.
For the extraction of bioactive compounds from the seeds, Tramontin et al. [20] used UAE (4 min, 70% power, and 20 kHz) and supercritical fluids extraction (SFE) with \( \text{CO}_2 \) (50 \(^{\circ}\)C, 12 MPa, 4.0 mL min\(^{-1}\) \( \text{CO}_2 \), and 150 min). In this study, the authors compared the performance of MAC, SOX, UAE, and SFE methods and concluded that the lowest yields corresponded to SFE at 50 \(^{\circ}\)C/20 MPa/3 mL min\(^{-1}\), obtaining 0.341 ± 0.008 mg GAE/g [20]. However, changing the processing conditions (50 \(^{\circ}\)C/12 MPa/4 mL min\(^{-1}\)) resulted in the third-highest value in the study, 0.937 ± 0.004 mg GAE/g. All the extraction methods used in this study had better yields when using ethanol as a solvent; additionally, ethanol extracts had better antioxidant capacity [20]. More recently, Olalere et al. [41] used microwaves-assisted extraction (MAE) in jackfruit seeds (5 min of irradiation, 450 W, and 50 \(^{\circ}\)C) and concluded that MAE produces high-quality extracts with a remarkable impact on properties like texture, phenolic exudation, and lower degradation of thermolabile compounds.

Jackfruit peel is considered an important source of pectin, thus some studies reported in the literature have focused on its extraction using emerging technologies. A couple of examples are the study performed by Xu et al. [34] using ultrasonic microwave-assisted extraction (1:48 \( w/v \), 86 \(^{\circ}\)C, and 29 min) and the one by Moorthy et al. [33] utilizing UAE (15:1 mL/g, pH 1.6, 24 min, and 60 \(^{\circ}\)C). When comparing the results from these investigations, the UMAE showed better performance than the UAE regarding pectin extraction yield. Naik et al. [19] applied radio frequency-assisted extraction (RFAE), which, compared with all methods previously described for pectin extraction, showed the highest pectin yield with 29.40%.

4. Functionality and Application of Functional Ingredients from Jackfruit

4.1. Health Benefits

Several studies have highlighted the health-related benefits of functional ingredients from jackfruit; some of them are related to helping mitigate diseases associated with oxidative stress [29]. For example, peel extracts have shown a high radical scavenging capacity; additionally, they inhibit \( \alpha \)-glucosidase, a potential antidiabetic property that helps control blood glucose levels [16].

Reports on jackfruit pulp showed it has selective antimutagenic and antiproliferative activities, in addition to some compounds, such as carotenoids, reducing the risk of lymphoma cancer [42]. Similarly, Kumoro et al. [1] reported that phenolic compounds present in seeds, such as polyphenols, flavonoids, tannins, and phenolic acids, have antiproliferative capabilities in cancer cell lines such as lung (A549), breast (MCF-7), liver (HepG2), and colon (HT-29), obtaining similar result to those reported by Li et al. [43]. Swami et al. [3] showed jackfruit seeds contain a non-reducing sugar that has a prebiotic effect, conferring benefits to the bacteria in the digestive system by creating a better environment for their growth and activity. The same study revealed that lignans, isoflavones, and saponins, also present in jackfruit, have anti-cancer, anti-hypertensive, anti-aging, antioxidant, and antiulcer properties [3].

Furthermore, other phenolic compounds present in the jackfruit, such as artocarpesin, norartocarpetin, and oxyresveratrol, have remarkable anti-inflammatory activity by suppressing nitric oxide (NO) and prostaglandin E2 (PGE2) production [44]. Similarly, pharmacological studies on pectin present in jackfruit showed its antioxidant, anti-tumor, and anti-inflammatory biological properties [34]. Jackfruit is also a good source of vitamin C and vitamin A, for which it has shown antiviral, antibacterial, and a good aiding in preventing blindness caused by macular degeneration [45]. Additionally, as Cardona [45] reported, its potassium content may help prevent cardiovascular accidents and reduce the heart attack risk by lowering blood pressure. Swami et al. [3] showed that jackfruit could help strengthen bones owing to its high content of magnesium, an essential nutrient in the calcium absorption process that works synergistically to strengthen and prevent bone-related disorders. Thanks to the positive health effects offered by the properties of jackfruit described above, different industries have focused on taking advantage of them.
Babu et al. [13] researched oil extracted from jackfruit seeds, showing that it is rich in EFA (1.35 g/100 g), including alpha-linoleic acid and linoleic acid, which stood out for its antioxidant properties. EFA help the proper functioning of the body, especially the brain, nervous system, adequate production of hormones, and other regulatory processes such as blood circulation, which helps prevent chronic diseases [13].

4.2. Applications

4.2.1. Pharmaceutical Industry

Some of the most relevant applications for the functional ingredients present in jackfruit are related to the pharmaceutical industry. The antioxidant properties of phenolic and carotenoid compounds, in addition to the anti-inflammatory properties of flavonoids and the antibacterial effects of extracts obtained from different parts of jackfruit, are of great interest owing to their potential incorporation into [4], for example, therapeutic agents for treating infectious diseases and their potential health benefits by positively affecting heart’s function, conditions of the skin, and prevention of ulcers and cancer development [3].

The jackfruit seed crude extracts contain jacalin, a type of lectin that presents a high affinity to the Thomsen–Friedenreich disaccharide antigen (Galβ1-3GalNAc), specifically its O-glycoside [3]. This protein also recognizes and reversibly binds to galactose [31]. Jacalin is suitable for studying O-linked glycoproteins and evaluating the immune system of patients infected with certain viruses, especially the human immunodeficiency virus 1 (HIV-1) [3]. Based on jacalin’s ability to target overexpressed disaccharides in tumor cells, Arya et al. [46] reported the development of surface-modified gold nanoparticles containing inositol hexaphosphate (IP6) and jacalin to maximize the apoptotic effect of IP6 against lines colon cancer cells (HCT-15). Their results showed significant apoptotic effects, concluding that the findings may raise the hope for a new drug delivery strategy to attack colon cancer [46].

In the case of jackfruit pectin, a multifunctional polysaccharide, its applications include usage as a binder for tablet formulations and as a versatile delivery agent for encapsulating drugs [47]. Govindaraj et al. [48] generated pectin (P)/hydroxyapatite (P/HA) bionanocomposites hybrids. These authors tested their cytocompatibility, alkaline phosphatase (ALP), anti-inflammatory activity, cell adhesion, and effects on fibroblast stem cells to establish their biocompatibility and feasibility as a bone graft [48]. On the other hand, Nayak & Pal [49] developed calcium pectinate-jackfruit seed starch mucoadhesive beads containing metformin HCl to evaluate the encapsulating effects of the drug and its cumulative release after some time. This study found positive effects on the yields, mucoadhesivity, and a significant hypoglycemic effect in diabetic rats after oral administration [49].

4.2.2. Food Industry

Regarding its applications in the food industry, some reports showed jackfruit and its derivatives (peel, seed, flour, chips, and wafers, among others) as functional foods thanks to their antioxidant proper, anti-cancer agents, and effect against the skin and vascular diseases [3]. Thanks to their properties, jackfruit bulbs can be used as ingredients for many foods and beverages such as jams, juices, concentrates, wines, and functional drinks, among others [50]. Further, their compounds can act as food flavoring or coloring agents [51]. Other studies report the combination of jackfruit pulp with other fruits like palmyra palm (Borassus flabellifer L) and passion fruit (Passiflora edulis Sims) to make functional beverages with a high content of bioactive compounds [52]. In a study regarding the optimization of jackfruit nectar’s processing conditions with a thermo-ultrasound, researchers found final nectar properties to be as follows: ascorbic acid content of 420 mg/L, total phenolics of 134 mg GAE/L, antiradical activity assayed with ABTS of 3.51 µmol Trolox Equivalents (TE)/L and with DPPH of 75 µmol TE/L, and residual activity of pectin methylesterase of 60% [53]. In addition, thermo-ultrasound proved to be effective as an alternative to pasteurization and generate good product quality [53].
Odoemelam [54] reported that jackfruit seed flour could be used as a functional ingredient as it helps to reduce the concentration of gluten in baked goods. Thanks to their antimicrobial properties, nanoparticles generated from jackfruit seeds were proposed as agents against foodborne pathogens [3]. Reported research results on improving chocolate cream properties by incorporating jackfruit flour showed a significant increase in the content of polyphenols (127.00 mg/g), carotenoids (160.16 mg/g), and antioxidant activity IC50 (42.75 μg/mL), while positively affecting the product's sensory properties such as viscosity and color [55].

Regarding jackfruit pectin, some possible uses in the food industry are as a gelling agent, emulsifier, stabilizer, and thickener agent in preparing jams, marmalades, and substitue for fats in various food formulations [19]. Meethal et al. [56] prepared snack bars using jackfruit seed flour and tested different formulations to compare their physicochemical, sensory, and nutritional changes during storage. Their results showed that the highest phenolic content in their formulations was 44.94 ± 0.21 mg GAE/g, while the highest antioxidant activity was 59.34 ± 0.26%, concluding that a jackfruit seed meal is a low-cost option for the preparation of value-added nutritional products [56].

4.2.3. Other Applications

Other applications mentioned for the bioactive compounds present in jackfruit include the cosmetic industry, such as using pectin to fabricate nanoparticles with emulsifying capabilities [57]. However, there is almost no research in other applications areas apart from the food and pharmaceutical industry, representing an area of opportunity for future investigations research.

5. Conclusions and Future Perspectives

According to the reviewed scientific research, it can be concluded that the quantity and quality of the compounds extracted from jackfruit depend on several factors. The main factors to consider are the extraction method, whether assisted by any emerging technology or not, the conditions of extraction, and the properties of the matrix used.

Regarding the performance of the technologies reviewed, the conventional technology with the best performance for recovering of phenolic compounds was alkaline hydrolysis extraction using NaOH in pulp samples. Additionally, extraction with methanol at 90% using peel as a matrix had the second higher total phenolic content. From the emerging technologies extraction reports, the best results were for SFE with CO₂ using jackfruit seeds. Concerning the application of emerging technologies as a pre-treatment, even though they may have not necessarily improved yields of extraction, their use can be beneficial for other aspects, such as process sustainability, by decreasing the use of organic solvents, shortening extraction times, and reducing the amount of energy consumed. However, more research is required to understand the effect of other emerging technologies, alone and in combination, when extracting these compounds.

Other research opportunity areas include the following: (1) determining the most convenient technology for carotenoid extraction from jackfruit, (2) applying non-conventional assisted extraction for functional ingredients present in jackfruit pulp, and (3) evaluating conventional and emerging technologies extraction methods for essential fatty acids in jackfruit need. Moreover, future studies should consider other jackfruit varieties/species and compare results based on their place of origin. The application of jackfruit functional ingredients also requires more investigation, not only for the food and pharmaceutical industries, but also for other areas such as the cosmetic area.

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