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Article *in* Asian Food Science Journal · August 2021

DOI: 10.9734/afsj/2021/v20i930346

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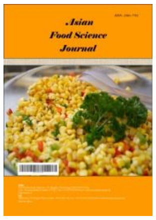

Asian Food Science Journal

20(9): 97-117, 2021; Article no.AFSJ.72518
ISSN: 2581-7752

Exploring the Potential of Jackfruit (*Artocarpus heterophyllus Lam*)

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Authors' contributions

This work was carried out in collaboration between both authors. Author SN designed the study, managed the literature searches, wrote the protocol and wrote the first draft of the manuscript. Author JHM reviewed and edited the manuscript. Both authors read and approved the final manuscript.

Article Information

DOI: 10.9734/AFSJ/2021/v20i930346
Editor(s):
(1) Dr.Surapong Pinitglang, University of the Thai Chamber of Commerce, Thailand.
Reviewers:
(1) Yadav KC, Tribhuvan University, Nepal.
(2) Abdela Befa, Ethiopia.
Complete Peer review History: https://www.sdiarticle4.com/review-history/72518

Systematic Review Article

Received 14 June 2021
Accepted 17 August 2021
Published 20 August 2021

ABSTRACT

Background: Jackfruit (*Artocarpus heterophyllus Lam*) is widely cultivated in tropical and sub-tropical areas worldwide. The tree is highly productive, resilient, and requires minimal care. Jackfruit has a characteristic flavour and is highly versatile. Several studies report the importance of the tree and fruits, ranging from food and medicine to the provision of several value-added products. In spite of the many benefits the plant offers, it has not been sufficiently incorporated in the general food system, partly because of gaps in processing, distribution and knowledge about utilization methods and nutritional and nutraceutical value.
Objective: A comprehensive literature search was done to highlight jackfruit's nutritional, health, and commercial benefits to promote its utilization.
Methodology: The literature search was conducted using three electronic databases with no constraints on publication year. Over 200 studies on the nutritional properties of jackfruit and at least 105 articles on the use of the various parts of the jack tree for their anticarcinogenic, antimicrobial, antifungal, anti-inflammatory, and hypoglycemic effects were found.
Findings: Jackfruit has vital nutrients, including phytochemicals, minerals, vitamins, carbohydrates, and proteins. The literature on utilization shows that the fruit can be processed into commercial products using minimal processing technologies, dried to extend product shelf-life, or processed into various value-added products.

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Conclusions: Jackfruit production and value addition are relatively under-developed despite the fruit tree's high yield potential, high nutritional value, nutraceutical and techno-functional properties. For improved benefits from jackfruit, actors need to adopt the available technologies at different value chain nodes.

Keywords: Jackfruit; nutritional benefits; processing; value addition.

1. INTRODUCTION

The jackfruit tree (*Artocarpus heterophyllus Lam*), also known as 'Jaca' in Brazil and USA, 'Jackfrutchbaum' in German, 'Nangka' in Malaysia, 'Fenesi' in Swahili and 'Ffenensi' or 'Ffene'in Uganda is believed to have originated from India [1]. The fruit is mainly cultivated in tropical and sub-tropical countries, especially Thailand, Malaysia, Brazil, Sri Lanka, Bangladesh, Burma, Philippines and Indonesia [2–5]. The jackfruit tree also grows in African countries, including Uganda, Kenya and Tanzania [6]. The jackfruit tree is medium-sized with a height of 8 to 25 m, and it bears one of the largest edible fruits in the world, which can weigh up to 80 kg. Depending on the variety, cultural practices, and environmental factors, the tree can produce 50-80 tons of fruit per hectare annually, a higher yield than any other tree species [7–10]. The tree performs well in diverse conditions, even under marginal soils and extreme climatic conditions [11].

The characteristics of jackfruit were described in detail by Ranasinghe et al. [12]. The whole fruit itself is typically ovoid to cylindric and is averagely 30–40 cm in length. Depending on the variety, the ripe fruit has bulbs that are white, orange or yellow. Jackfruit seeds are pale brown coloured, ovoid, and approximately 1-1.5 cm in diameter and 2-3 cm in length [13]. They are encircled by the fleshy bulb and encased in a white sheath surrounding a thin brown spermoderm.

Elevitch & Manner [11] highlighted several uses of parts of the jackfruit tree, including the seeds, bark, root, leaves and latex. Jackfruit bulbs are consumed in various forms, at both immature and mature stages. The seeds can be cooked whole or processed into flour for baking [1]. The tree is also recognised for its strong and sturdy timber. The wood chips also yield a dye that can be used to colour clothing [1]. The leaves and unused fruit can be used as fodder for cattle, pigs and goats. Jackfruit inedible parts have also been explored for their potential use in the production of biogas, briquettes and biochar, and pectin extraction [14,15]. In addition, nearly all plant parts, including bark, roots, leaves and fruits, possess therapeutic properties [16].

In spite of the numerous uses of jackfruit, it remains among the under-used crops in many countries [17]. Jackfruit could improve food security and poverty reduction in rural and urban communities [18]. This review summarises the research efforts and findings on the composition of the different parts of jackfruit as documented by various researchers and highlights the potential for processing and utilising jackfruit.

2. METHODOLOGY

A comprehensive literature search was done to highlight the information on jackfruit's nutritional, health, and commercial benefits. The literature search was conducted using three electronic databases (Google Scholar, ScienceDirect and Wiley online library). Search syntaxes including 'jackfruit/ *Artocarpus heterophyllus* and composition', 'jackfruit /*Artocarpus heterophyllus* and nutrition', 'jackfruit/ *Artocarpus heterophyllus* and medicinal properties', 'jackfruit/ *Artocarpus heterophyllus* and processing', 'jackfruit seed' and 'jackfruit/ *Artocarpus heterophyllus* 'utilization' without a restriction on the publication year were used. The first 300 papers from the databases, as suggested by Haddaway et al. [19], were assessed for data extraction suitability based on relevance, first by abstract, then by complete article analysis. Supplementary searches required to elucidate some content on jackfruit were also conducted and included in the review. In total, one hundred and forty articles were selected for inclusion in this review.

2.1 Nutritional Benefits of Jackfruit

Jack fruit is abundant in several nutrients (Table 1) and has many health benefits. The data show that mature jackfruit flesh and seeds contain more protein, calcium, iron, and thiamine than other tropical fruits like avocado, pineapple, mango, watermelon, and banana. The fruit contains substantial B vitamins, vitamin C, potassium, calcium, iron, proteins and carbohydrates [13].

Table 1. Proximate composition of jackfruit pulp and seed (100 g edible portion-fresh weight basis)

Nutrients	Young fruit[1]	Ripe fruit[1]	Seed[1]	RDA[2]
Water (g)	76.2–85.2	72.0–94.0	51.0 - 64.5	
Protein (g)	2.0–2.6	1.2−1.9	6.6-7.04	46-56
Fat (g)	0.1−0.6	0.1−0.4	0.4-0.43	44-77
Carbohydrate (g)	9.4–11.5	16.0–25.4	25.8 -38.4	130
Fiber (g)	2.6−3.6	1.0–1.5	1.0-1.5	28-33.6
Energy (kJ)	50−210	88−410	382*	8,400

[1][20] [2]Recommended Daily Allowance
** % Dry Matter*

2.1.1 Carbohydrate content

Carbohydrates are the most substantial food component derived from plants. Carbohydrate content varies in fresh fruits, ranging between 10 to 25% [21]. Khakimov et al. [22] found that the most abundant macronutrients in jackfruit grown in Tanzania were carbohydrates. Shafiq et al. [23] also established the nutritional profile of dried jackfruit, showing that it is a good source of carbohydrates (13.08%) and a considerable amount of crude fibre. This is in agreement with Eke-Ejiofor [24] and Ubi et al. [25]. Ojwang et al. [26], on the other hand, established that the carbohydrate content of the jackfruit pulp from selected regions in Kenya and Uganda ranged from 21.65% to 24.91%. These differences could be attributed to genetic variations in the jackfruit analysed by the different authors. Jackfruit contains substantial amounts of simple sugars like fructose, glucose and sucrose and is considered a high energy fruit [22,27].

2.1.2 Protein content

In contrast to other tropical fruits, jackfruit has a higher protein content (1.72 g/100 g edible portion), followed by banana (1.09 g/100 g edible portion), mango (0.82 g/100 g edible portion), and pineapple (0.54 g/100 g edible portion) [28]. Shafiq et al. [23] established the nutritional profile of dried jackfruit, showing that it contains a considerable amount of protein (1.48%). This is in agreement with Eke-Ejiofor [24] and Ubi et al. [25]. The amount of protein in the edible pulp of various jackfruit varieties reported by Goswami et al. [29] ranged from 0.57% to 0.97%.

2.1.3 Fat content

Lipids constitute only 0.1 to 0.2% of most fresh fruits [21]. Shafiq et al. [23] established the nutritional profile of dried ripened jackfruit, showing that it is a potential source of crude fat (5.63%). Khakimov et al. [22] found that total fatty acids contributed to around 10% of all nutrients in Tanzanian grown jackfruit. Palmitic and stearic acids emerged as the most abundant fatty acids. Chowdhury et al. [27] found palmitic and oleic acids to be the most abundant fatty acids in the edible part of jack fruit.

2.1.4 Mineral content

Sampath et al. [30] determined the mineral composition of different jackfruit genotypes. The authors established that the potassium content ranged from 231.43 mg/100 g to 332.33 mg/100 g. Potassium in jackfruit has been found to help in reducing blood pressure [31]. Potassium is also important in modulating various body processes, including but not limited to acid-base balance, nerve conduction, and muscle contraction. Calcium was present in the range of 28.04 mg/100 g to 47.95 mg/100 g. The magnesium concentrations ranged from 12.83 mg/100 g to 22.03 mg/100g. Calcium is required for mineralisation and essential for bone growth [30]. Magnesium facilitates calcium absorption and acts along with it to help strengthen bones and prevent bone disorders such as osteoporosis [32]. Sampath et al. [30] established that the copper content of jackfruit pulp was between 0.21 mg/100 g and 0.45 mg/100 g, and the iron content was between 2.28 mg/100 g and 4.23 mg/100 g. Iron helps to prevent anaemia and helps in proper blood circulation [33]. The manganese content ranged from 0.44 mg/100 g to 0.92 mg/100 g, while the zinc content was from 0.32 mg/100 g to 1.62 mg/ 100 g (Sampath et al., 2019). These findings were in agreement with Amadi et al. [34], who established jackfruit pulp's calcium and potassium contents at 30mg/100g and 330 mg/100g, respectively. However, the manganese and zinc contents in the same study were higher at 12.75 mg/100g and 5.20 mg/100g, respectively. The health benefits of zinc were articulated by Jarosz et al.

[35]. These include; proper functioning of the digestive and immune systems, diabetes management, energy metabolism, acne and wound healing. Ojwang et al. [26], in their analysis of jackfruit pulp from selected regions in Kenya and Uganda, established that potassium was the most abundant mineral. In contrast, copper and zinc had the least concentrations. The mineral analysis had the following trend; K (2836.66mg/100g) >Na (185.33mg/100g), >Ca (141.67 mg/100g), >Mg (76.28 mg/100g), >Fe 14.05mg/100g), with Cu (2.21 mg/100g) and Zn (5.31mg/100g) having the least concentrations. These values were considerably higher than the studies by Sampath et al. [30] and Amadi et al. [34]. Table 2 shows how the jackfruit elemental composition compares with other tropical fruits.

2.1.5 Vitamin content

Vitamins are a group of organic compounds needed in minimal amounts to support the body's normal development and functioning [36]. They are not synthesised by the body or are synthesised in insufficient amounts and are principally obtained by diet [37]. Jahan et al. [38] established the vitamin C content of jackfruit pulp at 35.32 mg/100g of edible portion. Conversely, the vitamin composition of jackfruit pulp was analysed by Amadi et al. [34], who established vitamin C content at 2.11 mg/100 g. Balamaze et al. [39] reported ascorbic acid contents ranging from 1.6 mg/100 g to 4.3 mg/100 g depending on the variety and fruit section. Ranasinghe and Marapana [13] studied the changes in vitamin C content at four maturity stages of the jackfruit flesh. They established that Vitamin C content increased with maturity at 2.18 mg/100 g immature to 8.17 mg/100 g fully mature. Effiong and Harry [40] found 0.073 mg of riboflavin, 0.138 mg of thiamine, 146 IU of vitamin A, 18.35 mg of vitamin C, and 12.75 mg niacin in jackfruit juice. Varietal differences, differences in the methods of extraction and analysis, age at harvest, and differences in processing methods could explain the variations observed between the vitamins content of jackfruits reported by different researchers. Table 3 shows how the vitamin content of jackfruit compares with other selected tropical fruits.

2.1.6 Phytochemical content

Phytochemicals, also known as phytonutrients, are non-nutritional plant chemicals that have disease protection or prevention properties. Most foods contain phytochemicals, particularly fruits and vegetables [41]. Many epidemiological studies have found a significant link between fruit and vegetable consumption and the low risk of many illnesses. Phytochemicals are associated

Table 2. Elemental profile of selected tropical fruits compared to jackfruit (100 g edible portion)

Nutrient	Jackfruit	Pineapple	Mango	Banana
Calcium (mg)	24	13	11	-
Iron (mg)	0.23	0.29	0.16	0.26
Magnesium (mg)	29	12	10	27
Manganese (mg)	0.043	0.927	0.063	0.27
Phosphorous (mg)	21	8	14	22
Potassium (mg)	448	109	168	358
Sodium (mg)	2	1	1	1
Zinc (mg)	0.13	0.12	0.09	0.15

Source: [28]

Table 3. Vitamin profile of jackfruit compared with other selected tropical fruits (100 g edible portion)

Nutrient	Jackfruit	Pineapple	Mango	Banana
Thiamine (mg)	0.105	0.079	0.028	0.031
Riboflavin (mg)	0.055	0.032	0.038	0.073
Niacin (mg)	0.92	0.5	0.669	0.665
Pantothenic acid (mg)	0.235	0.213	0.197	0.334
Vitamin B6 (mg)	0.329	0.112	0.119	0.4
Folate (µg)	24	18	43	20
Vitamin C (mg)	13.8	47.8	36.4	8.7

Source: [28]

with the prevention of several non-communicable diseases, including cancer, diabetes, osteoporosis, cardiovascular diseases (CVD), and vision diseases [42,43].

According to Lee et al. [44], jackfruit has superior phytonutrient content, including lignans, isoflavones and saponins that provide anti-cancer and anti-ageing properties and slow down the deterioration of cells that can lead to degenerative diseases. Lee et al. [44] established that caffeic acid was the predominant phenolic acid (0.221 mg GAE/kg fresh weight) of jackfruit followed by p-coumaric acid (0.164 mg GAE/kg fresh weight) and ferulic acid (0.127 mg GAE/kg fresh weight). Caffeic acid has anti-oxidant and antibacterial properties in vitro, and it can aid in the prevention of cardiovascular diseases. The acid also acts as a carcinogenic inhibitor [45].

Nyiwa [46] determined the phytochemical profile and phenolic contents of jackfruit leaves using thin-layer chromatography and spectrophotometric methods. Flavonoids, phenolic acids, coumarins, anthraquinones, anthocyanins, and terpenoids were present, while alkaloids were not found. ABTS and DPPH assays demonstrated that leaf extracts could scavenge free radicals connected with their IC50 values ranging from 17.26 ± 1.66 to 152.1 ± 30.20 mg/ml. The findings indicated that the antihelmintic and antioxidant activities of jackfruit leaves support the potential therapeutic interest of this species and could justify its use in traditional medicine. Table 4 shows the phenolics and carotenoids content of jackfruit compared to other selected tropical fruits.

2.2 Medicinal Benefits of Jackfruit

Numerous studies have reported the therapeutic benefits of jackfruit and, in particular, the various sections of the jackfruit tree, including the fruit. The sections below highlight some of the medicinal and other health benefits of jackfruit.

2.2.1 Anti-diabetic activity

While research exploring in detail the anti-obesity and anti-diabetic effects of jackfruit is rare, early solid results suggest jackfruit's potential for managing diabetes and obesity. Fernando et al. [31] found that giving jackfruit extracts to normal and diabetic patients at an oral dose of 20 g/kg of starting material resulted in a substantial increase in glucose tolerance. Biworo et al. [48] evaluated the anti-diabetic activity of jackfruit extract by inhibition of haemoglobin glycation method. This study showed that increasing jackfruit extracts concentration increased the haemoglobin glycation concentration and found the IC50 of jackfruit extracts to be 56.43%, suggesting that jackfruit extract is a potential anti-diabetic agent.

2.2.2 Anti-cancer properties

Ruiz-Montañez et al. [49] investigated the antimutagenic and antiproliferative ability of jackfruit pulp extract using *Salmonella typhimurium tester strains* TA98 and TA100 with metabolic activation (S9) and murine B-cell lymphoma. The jackfruit pulp extracts reduced the multiplication of cells M12.C3.F6 and the number of revertants caused by aflatoxin B1 (AFB1), showing a dose-response relationship.

These findings suggest that the pulp contains compounds that have properties that may prevent or treat lymphatic cancer.

2.2.3 Anti-inflammatory properties

Some phytochemicals in jackfruit have antiviral, antimalarial and anti-inflammatory properties [50]. Three phenolic compounds, artocarpesin, norartocarpetin, and oxyresveratrol, were extracted from the ethyl acetate fraction of jackfruit fruit by Fang et al. [51]. Strong anti-inflammatory properties after inhibiting lipopolysaccharide-activated (LPS) RAW 264.7 murine macrophage cells were exhibited by all three compounds.

2.2 4 Anti-ulcer and nephroprotective activity

Bhattacharjee and Dutta [52] studied the effect of methanolic and aqueous extracts of jackfruit tree bark on hard liquor and pylorus ligation induced ulcers in rats. The hard liquor induced ulcer and pylorus ligation induced ulcer showed a dose-dependent reduction by 100 and 200 mg/kg body weight doses, respectively. Another study by Bhattacharjee and Dutta [53] found that the aqueous and methanolic extracts of jackfruit tree bark have nephroprotective effects. This was confirmed by the decreased damage that appeared in the kidney tubules of treated rats which revealed recovery of many tubules from the nephrotoxic effect produced by gentamicin. These results suggest that the plant contains phytoconstituents which can enhance erythropoiesis by increasing the level of erythropoietin synthesised by the kidney.

Table 4. Phenolics and carotenoids content of jackfruit compared with other fruits

Fruit	Phenolics	Carotenoids
Jackfruit	0.18 to 0.46(mg GAE/g)[1]	1.32 (µg/g FW)[2]
Banana	3.9 to 4.1(µg GAE/g DW)	266.5(µg/g DW)
Mango	0.15 to 5.25 (mg GAE/g DW)	5.23(µg/g FW)
Papaya	1.8 to 1.72 (mg/g FW)	1.30 to 62.14(µg/g FW)
Passion fruit	132 to 2053 (mg/g FW)	0.14 to 0.25(mg/g FW)
Pineapple	0.25 to 0.73(mg GAE/g FW)	0.30 to 2.44 (β-Carotene) (µg/g FW)

Source: [47]
FW: Fresh Weight
DW: Dry Weight

2.2.5 Antimicrobial activity

A comparative study by Nagala et al. [54] documented the antimicrobial activities of essential oils from jackfruit seeds to explore their suitability for ethnomedical uses. Crude hexane and methanolic oils were found to show good to moderate activity against bacteria, in particular, Gram positive (*Bacillus cereus*, *Bacillus subtilis* and *Staphylococcus aureus*), Gram negative (*Eschirichia coli* and *Pseudomonas aeruginosa*) and fungal stains, more specifically *Aspergillus niger*, *Aspergillus flavus*, *Candida albicans* and *Saccharomyces cerevisiae*. Higher antimicrobial activity was observed on bacterial strains compared with fungal strains. Similarly, Theivasanthi and Alagar [55] proved the antibacterial effect of jackfruit seeds particles against *E. coli* and *B. megaterium.*

2.2.6 Other health benefits

Tyagi [57] documented the medicinal uses of parts of jackfruit, including the roots and leaves. Jackfruit root extract can be used to treat skin diseases, asthma and diarrhoea while jackfruit leaf extract and latex may cure asthma, prevent ringworm and heal cracked feet. Ash from jackfruit leaves is commonly used as a treatment for ulcers [20]. Crushed inflorescences are used to stop bleeding in open wounds, and extracts from fresh seeds aid digestion and cure diarrhoea and dysentery. Bark extracts also help cure dysentery while the ash produced by burning bark can cure abscesses and ear problems. Jackfruit latex mixed with vinegar promotes healing of abscesses, snakebites and glandular swellings. The wood has sedative properties; its pith is purported to facilitate abortion [58].

According to Prakash et al. [59], jackfruit leaves contain compounds such as morin, dihydromorin, cynomacurin, artocarpin, isoartocaepin, cyloartocarpin, artocarpesin, oxydihydroarto-carpesin, artocarpetin, norartocarpetin, cycloartinone, betulinic acid, artocarpanone and heterophylol that can help alleviate ailments such as fever, boils, wounds, skin diseases, convulsions and snake bites.

Jackfruit seeds contain two lectins; jacalin and artocarpin [60]. Jacalin has been proven useful for the elevation of the immune status of patients infected with human immunodeficiency virus 1 [61]. The seeds help lower the risk of heart disease, prevent constipation and promote weight loss, attributed to their high dietary fibre content and B-complex vitamins: jackfruit seeds also contain resistant starch, which regulates blood sugar and helps maintain gut health. In China and India, the seeds are used as antidotes for heavy alcohol drinkers [62].

2.3 Commercial Benefits of the Jackfruit Tree and Fruit

The jackfruit tree is of significant economic value. The fruits can be fermented and distilled to produce alcoholic beverages, including wines [63]. After removing the bulbs and seeds, the leaves and fruit waste are useful as fodder [1]. Additional benefits of the jackfruit tree were elaborated by Elevitch and Manner [11]. When it comes to furniture and musical instruments, jackfruit tree wood is generally considered better than many other types of wood. When the jackfruit latex is heated, it can be used as glue in chinaware and pottery. Clothing dye can be obtained by boiling the bark of the tree with alum. Jackfruit trees can be used as windbreakers; they may provide shade for other crops and help prevent soil erosion.

2.4 Jackfruit Processing

Fruit post-harvest losses in East Africa are as high as 30-40 per cent, resulting in a loss of potential income and nutrition [64]. The jackfruit flesh is highly perishable and suffers a loss of flavour, softening of the tissues and enzymatic browning over time [65,66]. The fruit is more prone to contusions and mechanical injuries due to tissue softening [67]. There have been ongoing efforts to reduce jackfruit losses and diversify utilization through processing into a wide range of convenient and shelf-stable products. Jackfruit is very versatile, and several studies have reported numerous value-added products from jackfruit bulbs, including nectar, juice, wine, yoghurt, powder, leather, crisps, dehydrated, frozen and canned products. Jackfruit seed has been used to make flour, extract starch [68] and oil [69], as well as protein [70].

2.4.1 Minimal processing technologies for jackfruit pulp

Minimally processed jackfruit remains in a fresh state but is physically transformed from its original form. The freshness, health benefits, and convenience of minimally processed fruits have increased the demand for jackfruit and other tropical fruits [71]. The shelf life of minimally processed products (MPPs) is between three to fifteen days, depending on the product, packaging, and storage conditions [72]. Appropriate minimal processing protocols for jackfruit bulbs could overcome problems related to decreased fruit quality, including loss of flavour, tissue softening, and surface browning. Minimal processing technologies can be employed at different stages, including pretreatments, packaging and storage [73]. Fig. 1 shows some minimal processing treatments for jackfruit pulp.

2.4. 2 Value-added products from jackfruit bulbs

The processing of jackfruit into value-added products improves the crop's potential for utilization both locally and internationally. Many products have been developed and studied from both ripe and unripe jackfruit, some of which are summarised below.

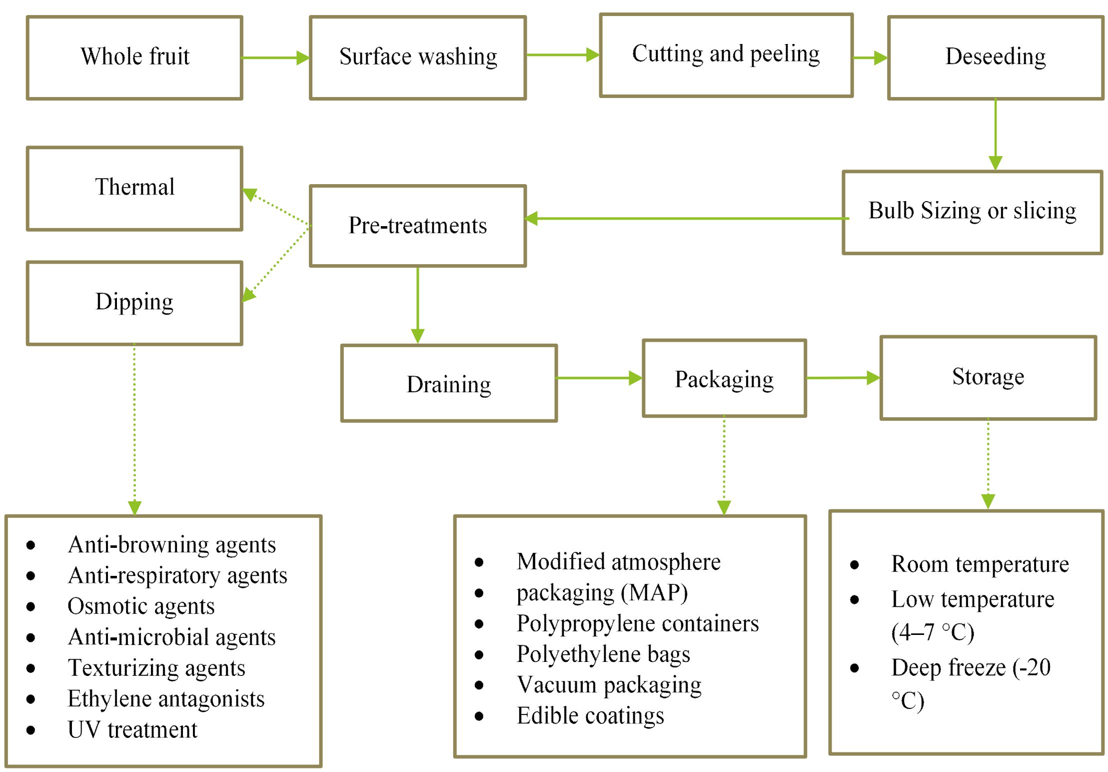

Fig. 1. Minimal processing treatments for jackfruit pulp [73]

2.4.2.1 Immature jackfruit

In many countries, immature or semimature jackfruits are used as vegetables, boiled and seasoned or mixed with other food. Immature jackfruit has a meat-like taste and is sometimes used in curry dishes mixed with spices and in meatless sandwiches [74]. The fruits can be cooked in coconut milk and eaten curried, mixed in milk to form a pleasant custard or pickled with or without spices [75].

2.4.2.2 Jackfruit chips

Jackfruit chips are a popular delicacy in South Asia [76]. According to Yi et al. [77], many processing technologies have been applied to produce fruit chips, such as deep-fat frying, vacuum frying, freeze-drying, steam puff drying, and microwave vacuum drying. Jagadeesh et al. [78] studied the potential use of twenty-eight different mature but unripe jackfruit types to prepare jackfruit chips. The authors theorised that while fruits of some jackfruit trees may be suitable for desserts, they may not be appropriate for processing due to variations in their biochemical composition. Starch and dry matter content, flake thickness, bulb length, total soluble solids, and reducing sugars were identified as parameters for consideration while selecting jackfruit genotypes to improve jackfruit chips yield and quality.

2.4.2.3 Jackfruit jam

Mushumbusi [6] produced and characterised jackfruit jam by extracting the bulbs from the jackfruits. The bulbs were then blended with water and boiled for 10 minutes, after which the juice was extracted. Seven kilograms of sugar and 670 ml lemon juice were added into 13 kg juice and cooked until the TSS was 69 °Brix. The endpoint was determined through a flake test. Jackfruit and mango jam samples were subjected to sensory evaluation. Jackfruit jam showed a higher score in hue (colour) and aroma compared to mango jam. Ihediohanma et al. [79], Tiwari et al. [80], and Mondal et al. [66] also studied the production of jam from jackfruit and concluded that the fruit could be used for jam making.

2.4.2.4 Jackfruit wine

Jackfruit is an excellent substrate for fermentation because it has high sugar content. The phytochemical content and anti-oxidant properties of wine produced from jackfruit pulp were evaluated by Jagtap et al. [63]. According to the findings, jackfruit wine was effective in 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging (69.44±0.34%), ferric reducing antioxidant power (FRAP) (0.358 optical density value, O.D.), N, N-dimethyl-p-phenylendiamine (DMPD) (78.45±0.05%) and nitric oxide (NO) (62.46±0.45%) capacity. Gallic acid and protocatechuic acid were identified through high-performance liquid chromatography coupled to diode array detector (HPLC-DAD) analysis [63]. When consumed, jackfruit wine is a valuable source of antioxidant-rich nutraceuticals due to its anti-oxidant and DNA damage protecting properties. Jackfruit wine compared favourably with other wines, including bilberry, blackberry, and black mulberry wines whose ability to scavenge free radicals when measured using DPPH was 61.80%; 60.00%; and 58.10%, respectively [81].

Sharma et al. [82] have studied the conditions which influence wine fermentation from jackfruit. Three parameters, including temperature, pH and inoculum concentration, were evaluated. Three temperatures (27°C, 32°C and 37°C), three pH conditions (4, 5, 6) and three inoculum concentrations (5%, 10% and 15%) were maintained. The authors hypothesised that the three variables influenced fermentation and discovered that 12-14 per cent alcohol content could be reached in two weeks, increasing to 19 per cent in the third week. The developed wine had strong anti-oxidant activity and had a sweet aroma, which added to its sensorial characteristics. Panda et al. [83] fermented wine yeast (*Saccharomyces cerevisiae*), as a starter culture, with jackfruit pulp to develop jackfruit wine. The wine exhibited good antioxidative properties, with phenol content at 0.78 g/100 ml, ascorbic acid at 1.78 mg/100 ml, β-carotene at 12 µg/100 ml and DPPH scavenging at 32%. The wine was well accepted according to sensory findings.

2.4.2.5 Jackfruit flavoured yoghurt

Kamalesh et al. [84] and Onik et al. [85] produced yoghurt from jackfruit juice. Kamalesh et al.(2014) used three different amounts of jackfruit juice and found that the proportion of 15% jackfruit juice with milk yoghurt had a slightly better taste owing to high acid content. Onik et al [85] developed yoghurt using eight different levels of jackfruit juice (2%, 4%, 6%, 6.5%, 7%, 7.5%, 8% and 10%). According to the sensory assessment, the jackfruit yoghurt formulated with 6.5 per cent jackfruit juice had the most acceptable colour, flavour, texture, taste preferences, and overall acceptability. However, the mean values of all parameters for the developed jackfruit yoghurt were not significantly different from plain yoghurt. Dissanayaka et al. [86] evaluated the nutritional, physicochemical and sensory properties of frozen yoghurt incorporated with jackfruit pulp at three levels, 10%, 15% and 20%. The protein content of all jackfruit flavoured frozen yoghurts was higher, and their fat content was lower than plain yoghurt. Their results also showed that both ash and fibre contents increased with more jackfruit pulp, the latter possibly because jackfruit is a good source of fibre. The analysed properties, including sensory attributes, improved significantly by adding jackfruit pulp at a rate of 15%. The authors surmised that jackfruit flavoured frozen yoghurt could be introduced as a value-added healthy dairy product.

2.4.2.6 Jackfruit flavoured ice cream

Ice cream is a popular frozen food, typically eaten as a snack or dessert. Ice cream is usually made from milk or cream and is often combined with fruits or other ingredients and flavours. The problem faced regarding the consumption of ice cream is its lack of nutrients such as vitamins, minerals and dietary fibre. Gaikwad et al. [87] and Rawendra and Dwi [88] hypothesised that the addition of jackfruit pulp could improve the phyisco-chemical or organoleptic qualities of ice cream products. The former concluded that the best quality ice cream could be prepared by adding 15 per cent jackfruit pulp. The latter established that the soft ice cream with 25% of jackfruit puree had the highest preference score of texture. Rawendra and Dwi [88] also established that the addition of jackfruit puree increased the viscosity, dietary fibre, protein, total solids, and fat content in soft ice cream.

2.4.2.7 Dried jackfruit

Dried fruits are important healthy snacks globally. They have the advantages of being compact, simple to store and distribute, year-round availability, and a healthy alternative to savoury and sweet snacks [89]. Drying jackfruit has several advantages, including longer product shelf life and off-season availability, reduced packaging, storage, handling and transportation costs while offering the possibility of adding value to the fruit [90]. Several researchers have studied the drying of jackfruit. Some drying methods applied to jackfruit include solar drying to make jackfruit leather [64], a combination of instant controlled pressure drop-assisted freeze-drying, instant controlled pressure drop assisted hot air drying, and freeze-drying to make jackfruit chips [76], hot air drying [91], osmotic dehydration [92,93], drum drying [94,95], osmo convective drying [96], freeze-drying [97], and convection oven drying [98]. These technologies differ in drying speed, energy efficiency, product quality, dryer costs, and technological simplicity. The main technical challenge is to identify a relatively inexpensive drying technology that gives high-quality products, even from heat-sensitive materials, as most drying technologies entail the application of high temperatures. This causes discolouration as well as the loss of flavour, nutrients, and bioactive compounds.

Refractance Window Drying, a novel drying technology, has recently been used to dry jackfruit with positive results (Unpublished data). Refractance window (RW) drying allows for concentration and drying of are liquid foods, purees or thin slices to obtain a flake or film [99]. The product is dried on one side of a thin plastic film known as Mylar® (DuPont Polyester Film Enterprise, Wilmington, DE). The other side is in intimate contact with hot water at temperatures below the boiling point. The thermal energy is transferred from the hot water through the film, which due to the low resistance to thermal conductivity, allows for quick evaporation of moisture from the product [100]. Refractance window drying has been used with positive results in drying mango [101], asparagus, and pumpkin [102], among others. Retention of colour, ascorbic acid, anti-oxidant activity, carotenoids and capsaicinoids have been reported by various studies on refractance window drying, compared with other drying methods such as spray drying. Furthermore, RW equipment costs about one-third of a freeze-dryer (FD), and RW uses less than half the energy that a freeze-dryer does to dry the same amount of product [103]. Refractance window technology has a number of advantages that make it a technology of choice for the production of high value dried products in developing countries.

2.4.3 Value-added products fortified with jackfruit seed flour

Various processing methods such as autoclaving, drying, roasting, boiling and germination can be used to convert jackfruit seeds into flour [104]. Akter and Haque [105] determined the proximate composition of the flour from jackfruit seeds, as shown in Table 5. Several studies on the use of seed flour as a food ingredient have been conducted. Some products prepared by fortification of seed flour are presented in Table 6.

Table 5. Proximate and micronutrient composition of jackfruit seeds flour

Properties	Values (% dry matter)	Micronutrients/ Other components	Jackfruit seed Flour (per 100 g)
Moisture	7.63	Calcium (mg)	77.3
Crude fat	1.11	Iron (mg)	0.59
Ash	2.35	Phosphorous (mg)	43.7
Protein	10.26	Potassium (mg)	14.7
Carbohydrate	78.65	Copper (mg)	1.04
		Manganese (mg)	0.12
		Neutral detergent fibre (g)	5.19
		Amylose (%)	20
		Amylopectin (%)	80
		Titratable acidity (%)	5.78
		Lactic acid (%)	1.12

Source: [105], [106]

Table 6. Products prepared from jackfruit seed flour

Product name	Supplementation (%)	Outcome	Reference
Bread	5	High protein and carbohydrate content, good water and oil absorption ability	[107]
Bread	25	Increased crude fibre content	[62]
Biscuit	20	Good water and oil absorption capacity, swelling power, solubility, flour dispersibility and viscosity	[62]
Biscuit	10-40	Increased moisture, fat, crude fibre and ash content	[108]
Cake	5-15	Increased protein and reduced fat content	[109]
Chocolate cake	5-15	Improved dietary fibre and anti-oxidant activity	[110]
Composite cake	10-30	Better crumb, texture and nutritional characteristics	[111]
Muffins	10-20	Increased specific gravity and decreased viscosity	[112]
Bread	25-55	Increased nutritional value and overall acceptability compared to the control and other samples	[113]
Biscuits	25 and 50	Higher acceptance scores for sensory characteristics.	[114]
Noodles	10-20	Higher yield ratio and lower cooking time	[115]
Fortified noodles	5	Higher protein, fat, fibre, ash content and better organoleptic properties	[116]
Noodles	5-15	Increased protein, iron, calcium and carbohydrate content.	[117]
Pasta	10	Increased nutrient content	[118]
Expanded snacks	10-40	Increase in nutritional and phytochemical properties	[119]
Cereal bar	30 and 40	High fibre content, better sensorial characteristics	[120]
Snack bar	35-45	Increased protein content	[121]

2.4.4 Value addition and utilization of jackfruit peel and perianth

The outer protective layer of the jackfruit, also known as the rind, peel or skin, is an underutilised by-product in both the production and processing of the fruit. Jackfruit peel is purportedly rich in starch, protein, pectin and cellulose, comprising about 4%, 6.27%,7.52% and 27.75%, respectively [122].

2.4.4.1 Extraction of bioactive compounds

Zhang et al. [123] used HPLC-QTOF-MS/MS to compare the anti-oxidant and hypoglycaemic ability of jackfruit peel to jackfruit pulp, flake, and seed. Jackfruit peel extract exhibited the highest total phenolic content; 4.95, 4.12 and 4.65 times higher than seed extract, flake, and pulp. Jackfruit peel extract also exhibited the highest DPPH· and ABTS+· scavenging ability, and α-glucosidase inhibition, with the latter about 11.8-fold of that of acarbose, an inhibitor of alpha-glucosidase and pancreatic alpha-amylase with antihyperglycemic activity.

Jiang and Wang [124] explored the use of ultrasonic microwave-assisted extraction in conjunction with macroporous resin chromatography to extract and purify anti-oxidant phenolics from jackfruit peels. The three most abundant phenolics derived from jackfruit peels were gallic acid, chlorogenic acid, and catechin. Zhang et al. [125] also established bioactive compounds, including prenylflavonoids, hydroxycinnamic acids, and glycosides, predominant in peel extract. The findings showed that jackfruit peels are a good source of phenolics with high anti-oxidant and hypoglycemic properties.

2.4.4.2 Animal feed

According to Ndyomugyenyi [126], the food grains produced in most developing countries are mainly intended for human consumption, resulting in a persistent shortage of animal feed. This has spurred a necessary dependence on alternative feeds to sustain livestock feeding. The jackfruit peel is a valuable raw material for cattle feed because it is high in carbohydrates, protein, and fibre [127]. Ndyomugyenyi [126] established that jackfruit seeds could be used as energy sources for poultry feeding. However, the study also found that seeds contain anti-nutrients such as triterpenes sterols and, which have to be eliminated before seeds are included in animal diets.

2.4.4.3 Bio-fuel

Biomass is one of the most viable sustainable alternatives to fossil fuels, with the added benefit of not leading to a net rise in CO_2 levels in the atmosphere [128]. According to Alves et al. [129], it is critical to allow for the partial replacement of fossil-based fuels in the future by increasing the use of biomass-based energy. They further note that renewable energy sources with a high capacity for bioenergy generation can help reduce emission levels, which is essential to sustainable development.

Jackfruit waste, which includes peels and seeds, generates about 2.96 million tons of potential feedstocks per year [129]. Physicochemical properties, bioenergy markers, combustion behaviours, and emission characteristics were all used by Alves et al. [129] to evaluate the suitability of peels and seeds as combustion feedstocks and their potential for bioenergy. The jackfruit waste presented attractive features for direct combustion applications, such as their composition of volatile solids, carbon content, a higher heating value, and negligible amounts of nitrogen and sulphur. Their ash contents were similar to that of other biomass fuels, and the bioenergy yield obtained for peels and seeds exceeded that of well-known bioenergy crops. Given the low CO, CO_2, and SO_2 emissions and a high equivalence with reference fuels, using jackfruit residues as a raw material for bioenergy could be very feasible. Combustion properties of seeds and peels revealed good burning performance. Soetardji et al. [130] used pyrolysis to extract bio-oil from jackfruit peel waste in a fixed bed reactor at high temperatures (400-700^{o}C) and investigated the extracted oil. The authors established that the peel contains a high percentage of volatile compounds, indicating that this biomass could make bio-oil. Low Sulphur (0.03%) and nitrogen (0.61%) contents, close to those found by Alves et al. (2020), were a good indicator that the bio-oil was environmentally friendly. The study found the best quality bio-fuel with the highest organic content (85.2%), and the lowest water content (14.8%) was obtained at 550^{o}C.

Yuvarani and Dhas [131] used Saccharomyces cerevisiae yeast as a microorganism to extract bio-ethanol from jackfruit peel. The impact of various parameters such as the composition of jackfruit peel, temperature, shaking rate, fermentation time, and nutrients was investigated, and conditions were optimised. The results showed that increasing the jackfruit peel composition increased ethanol extraction while increasing the temperature decreased it. These studies have provided data for the commercialisation and large-scale use of jackfruit wastes and their potential as sustainable and renewable energy sources.

2.4.4.4 Pectin extraction

Pectin is a complex polysaccharide extracted from plant materials found in higher plants' cell walls and middle lamellae [132]. Pectin is a functional ingredient in food and pharmaceutical applications because of its gelling, emulsifying, thickening, and stabilising properties [14]. Jackfruit peels are a potential source of pectin, as demonstrated by Ahmmed et al. [14]. The authors extracted pectin from jackfruit peel and core using water-based extraction methods at different temperatures (70, 80 and 90°C), pH (1.8, 1.9 and 2.0) and extraction periods (1.5, 2.0 and 2.5 h). When pectin was extracted at a pH of 1.9 and a temperature of 80°C for 2.0 hours, the yield was highest, with high purity and low ash content. The yield from jackfruit peel and core ranged from 6.0 to 14.0% on dry weight basis. The authors hypothesised that jackfruit pectin can be classified as low-methoxyl pectin based on its methoxyl content. It could, therefore, be used in low-sugar items, including jams and jellies.

Conventional boiling is the traditional method of extracting pectin, which takes more time and yields less pectin than other methods, including microwave and high-pressure extraction [133,134]. Naik et al. [135] demonstrated that the yield of pectin from jackfruit peels is enhanced, and extraction time is reduced by using radio frequency-assisted extraction under acidic conditions. Additionally, the process is efficient and environmentally friendly.

2.4.4.5 Packaging applications

According to Luchese et al. [136], plastic materials are used to manufacture approximately 40% of food packaging, which raises concerns related to poor disposal, non-biodegradability and recycling difficulty. Additionally, as these are usually single-use packaging materials, they have attracted increasing attention due to their potential to cause serious environmental problems [137]. In order to overcome these issues, biopolymers from renewable sources are considered an alternative since they are inexpensive, environmentally friendly, abundant, biodegradable and recyclable. Agricultural wastes, including seeds, peels and other by-products, are considered the most effective sources in this regard [136].

Sarebanha and Farhan [138] produced biodegradable films using jackfruit waste flour obtained from the rind of jackfruit. Different concentrations of jackfruit waste flour were mixed with polyvinyl alcohol composites using a solution casting method to prepare the composite films. The composite films' heat sealability, as well as their physical and mechanical properties, were investigated. The findings revealed that jackfruit waste flour could be used in food packaging materials to create environmentally friendly biodegradable flexible films, reducing the need for synthetic polymers in food packaging.

2.4.4.6 Juice preparation

Jackfruit waste, including the peel/rind and unfertilised floral parts, can be used to produce juice, as established by John and Narasimham [139]. The researchers developed a process for preparing a ready-to-drink juice from jackfruit rind, sheath, and unfertilised flowers, which produced about 60% yield of highly acceptable clarified juice. The authors hypothesised that the preparation of beverages from jackfruit waste would increase the utilization of jackfruit to over 80%, besides the processing of bulbs and seeds.

2.4.5 Value addition to jackfruit perianth

Approximately 25.35% of the jackfruit are rags (latex-like filaments that separate the fruit bulbs into compartments), which usually go to waste [140]. According to Subburamu et al. [127], the perianth, which includes the rags, contains valuable nutrients such as carbohydrates (28.9%), protein (10.3%) and crude fibre (12.7%). Dam & Nguyen [140] optimised the production of a jackfruit based fermented drink from the fruit rags. A beverage with acceptable sensory quality was obtained at 25^{o}C with a fermentation time of three and a half days, at a pH of 4.6.

2.5 Prospects for Improved Jackfruit Utilization

Considerable efforts have been made to convert waste and by-products into value-added products to counter the increasing pressure on existing resources. However, more concerted efforts are required to bolster appreciation of the crop and to increase its utilization. Some prospects for improved jackfruit utilization include the following:

- Increase the area, organisation and production of jackfruit and their processed products.
- Promote and commercialise modern low-cost processing technologies such as refractance window dying technology for processing and value addition of jackfruit to ensure fruit availability throughout the year and avoid the wastage of the fruit. This should go hand in hand with farmer and agroprocessors trainings on value addition in jackfruit.
- Promote large, medium and small scale jackfruit processing industries.
- Support consumer and retailer training about the nutritional and commercial benefits of jackfruit.
- Foster industry partnerships to promote and supply value-added production of jackfruit.
- Develop quality standards to ensure consistency of jackfruit and building capacity for value-added products as well as recipes and information on preserved and value-added jackfruit products.
- Develop technical and research resources for the jackfruit industry.
- To diversify available energy sources, encourage the use of jackfruit waste to produce biofuels such as biogas, briquettes, and biochar.

Implementation of these strategies will improve the fruit's spatial and temporal distribution, strengthen the jackfruit's position in food systems, and facilitate the development of the jackfruit value chain. Additionally, adoption of cost-effective jackfruit preservation technologies, alongside improvements in distribution, marketing and utilization of jackfruit, has the potential to lead to higher farm production, higher income for farmers, lower environmental footprint, improved nutrient intake, diversification of food value-added food products, creation of jobs and import substitution.

3. CONCLUSION

The research on consumption and use of the various parts of jackfruit is steadily increasing due to its documented uses. The rich nutrient and biochemical profile of jackfruit make it a highly desirable fruit tree with the potential to improve food insecurity, especially in less developed countries, more so because the tree is highly resilient and requires minimal care. Consumers can exploit the benefits of this fruit tree by utilising the broad spectrum of products it offers.

DISCLAIMER

The products mentioned in this research are commonly and predominantly used in the authors' area of research and country. There is no conflict of interest between the authors and producers of the products. The products mentioned are not intended for use as an avenue for litigation but for the advancement of knowledge. Also, the research was not funded by any producing company.

ACKNOWLEDGEMENTS

This work was funded by sida under the bioinnovate africa ii program and the fruits and vegetables for all seasons (fruvase) project through makerere university.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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