International Journal of Food and Fermentation Technology
Citation: *Int. J. Food Ferment. Technol.*, **16**(01): 243-261, June 2026
**DOI:** 10.30954/2277-9396.01.2026.18

ASSOCIATION FOR AGRICULTURE ENVIRONMENT AND BIOTECHNOLOGY

**REVIEW PAPER**

# Jackfruit Seed and its Physico-chemical Properties, Structure, Morphological and Functional Characteristics and Modifications of Jackfruit Seed Starch and its Recent Applications: A Review

Akshata Manish Gokhale and Shrikant Baslingappa Swami*

Department of Post-Harvest Engineering, Post-Graduate Institute of Post-Harvest Technology and Management, Killa-Roha. Dist: Raigad (Maharashtra State) (Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli-Campus Roha), India

*Corresponding author: swami_shrikant1975@yahoo.co.in

**Paper No.:** 361 **Received:** 06-04-2026 **Revised:** 08-05-2026 **Accepted:** 21-05-2026

**ABSTRACT**

As global food industries prioritize sustainable waste management, Jackfruit *(Artocarpus heterophyllus)* seed have emerged as a high-potential, underutilized agro-industrial byproduct for starch extraction. Although seeds account for up to 7-12% of the total fruit weight, they are traditionally treated as agricultural waste, making the extraction of jackfruit seed starch a highly sustainable and economically viable solution. Structurally, jackfruit seed starch is characterized by high amylose content of 22.10-38.34%, small granule size of ~ 7-11μm, high gelatinization temperature and an A-type crystalline structure, which altogether contribute to its excellent gelling stability and low digestibility. Nutritionally, its high resistant starch content offers significant health benefits, including low glycemic index properties. Due to these distinct traits, jackfruit seed starch is highly versatile; it is utilized in food industries as a thickener, stabilizer, frying batter modifier as well as in non-food industries for developing biodegradable bioplastic, intelligent packaging films and pharmaceutical binders. However, despite of its immense capabilities, research gaps remain regarding industrial scalability, extraction efficiency and market integration. This review paper consolidates the current state of knowledge on jackfruit seed starch, highlighting its functional variations and outlining future directions for its successful commercialization.

**Keywords:** Jackfruit seed starch, underutilized starch, physico-chemical properties, functional properties, food application, biodegradable materials.

Jackfruit seed typically discarded as a waste but it holds immense potential as a functional food due to their high nutritional value and health-promoting bioactive compounds. Botanically Jackfruit is *Artocarpus heterophylus* Lam. Numerous regions of Asia, Africa, and South America are home to this tropical fruit, which is a member of the Moraceae family (Dhani *et al.* 2025). Jackfruit area and production for the year 2024-25 in India were 186000 ha and 4198000 MT, respectively (Department of Agriculture and Farmer Welfare, 2024-25). The global starch market was estimated to be worth USD 60 billion (134.5 million metric tons) in 2022 and could reach USD 90 billion (200 million metric tons) by the end of the third decade, growing at a compound

**How to cite this article:** Gokhale, A.M. and Swami, S.B. (2026). Jackfruit Seed and its Physico-chemical Properties, Structure, Morphological and Functional Characteristics and Modifications of Jackfruit Seed Starch and its Recent Applications: A Review. *Int. J. Food Ferment. Technol.*, **16**(01): 243-261.

**Source of Support:** None; **Conflict of Interest:** None

annual growth rate (CAGR) of 5.1% between 2022 and 2030 (Globe Newswire). In Maharashtra State, the area and production of jackfruit were 540 ha and 7730 MT, according to the Department of Agriculture and Farmer Welfare, 2024–25. It was discovered that the edible section of the jackfruit yielded 25–35% carpel and 7–12% seed, whereas the non-edible portion (i.e. outer thick rind, rags and central core) made up 50–58% of the overall fruit. This suggests that jackfruit seeds accounted for 7–12% of total jackfruit production, with some consumed and the rest wasted. The consumption of jackfruit seeds is low and underutilized despite their availability, according to a study by Manianga *et al.* (2024). However, encouraging the semidry variety could help make them a useful, sustainable food option.

A variety of amino acids that are necessary for a healthy diet, including arginine, leucine, histidine, cystine, lysine, methionine, threonine, and tryptophan, are also found in jackfruit seeds. Jackfruit seeds contain bioactive substances including polyphenols, tannins, flavonoids, ferulic acid, gallic acid, and caffeic acid (Dhani *et al.* 2025).

There are different unconventional sources of starch like corn, potato, wheat, cassava, maize, rice, arrowroot, pulses, yam and chestnut used for extraction of starch in large amount (Fatima *et al.* 2024). These all starch are extracted from the staple food material, that causes changes in prices of staple food material. Significant amounts of arable land and intensive irrigation are frequently needed for conventional starch crops, which are unsustainable in areas with limited water resources. Due to the intensive farming higher carbon emissions, soil degradation occurs (Apoorva and Kundlas, 2024). Traditional starch crops grown in monoculture are more susceptible to pests, diseases, and climate change (Kaur *et al.* 2024).

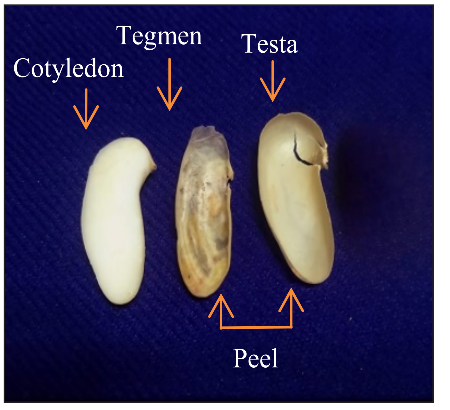
Now a day's jackfruit seed starch becomes a good alternative to the conventional starches. Jackfruit has required less agricultural input as compared to other sources, it is a tropical tree (Chikkanna, 2021). Compared to many conventional starches, jackfruit seed starch has greater heat stability, a strong gel-forming ability, and small, uniform granules, all of which are important functional characteristics for food and material applications (Brahma and Ray, 2023). Additionally, it has resistant starch about 75%, which is linked to health advantages like better gut health and decreased digestibility, making it appealing for food products with a health focus (Zhang *et al.* 2018; Kushwaha *et al.* 2023a). Jackfruit-rich areas can produce starch domestically, lowering reliance on imported starch and boosting regional rural economies. According to research, jackfruit seeds are underutilized in many rural areas, but they could be used to improve socioeconomic welfare and sustainable livelihoods through processing (such as the production of seed flour or starch), strengthen regional food systems and marketplaces (Manianga *et al.* 2024).

Jackfruit seed starch is now widely used in food as thickeners, gelling agents, and fillers in confectionery or weaning foods, pastry filling and gum, chili sauce and also for producing maltose syrup. Jackfruit seed starch is also used in developing biodegradable film and as a shell material for capsule (Zhang *et al.* 2021). In order to highlight jackfruit seed starch's potential as a sustainable substitute starch source, this review attempts to critically compile current knowledge on its extraction, characteristics, modification, and uses.

**Jackfruit seed Structure and morphology**

Typically the jackfruit seed is in oval, oblong, or elliptical in shape. The jackfruit seed is surrounded by a white testa and a thin brown endosperm, which encases a fleshy white cotyledon. After drying the testa become rigid but during wet condition the testa is thin and leathery, while inside the testa, there's a delicate skin that looks slightly brown in color. The hilium, located near the micropyle, thickens the seed. The cotyledons are similar in size, differing only slightly, and the endosperm is small, with the embryo featuring a surface radicle (Neelanjana, *et al.* 2023; Brahma and Ray, 2023). The physical properties of jackfruit seed of two different forms studied by Deshmukh, and Swami, 2022 is given in Table 1

(a) Longitudinal Section of Jackfruit Seed




(b) Peel over the cotyledon

**Fig. 1:** Structure of Jackfruit seed **(a)** Longitudinal Section of Jackfruit Seed; **(b)** Peel over the cotyledon

**Table 1:** Physical properties of jackfruit seeds of two forms i.e. Kapa and Barka

| Sl. No. | Physical Parameter (Deshmukh, and Swami, 2022) | Kapa (Moisture content 9.433 % db) | Barka (Moisture content 11.37 % db) |
|---|---|---|---|
| 1 | Length (L) | 23.13 mm | 23.85 mm |
| 2 | Width (W) | 13.10 mm | 13.84 mm |
| 3 | Thickness (T) | 9.857 mm | 10.05 mm |
| 4 | Geometric mean Diameter (*Dp*) | 14.01 mm | 14.63 mm |
| 5 | Sphericity (Φ) | 0.606 | 0.608 |
| 6 | Surface area (S) | 620.00 $mm^2$ | 662.28 $mm^2$ |
| 7 | True density ($\varrho t$) | 383.7 $kg/m^3$ | 362.9 $kg/m^3$ |
| 8 | Bulk density ($\varrho b$) | 829 $kg/m^3$ | 844 $kg/m^3$ |
| 9 | Porosity (P) | 53.71 % | 57.00 % |
| 10 | Angle of repose (θ) | 57.34° | 58.39° |

*Deshmukh, and Swami, 2022.*

below. Also the Table 2 shows the composition of jackfruit seed. Also the Fig. 1 shows the structure of jackfruit seed.

**Different methods of jackfruit seed starch extraction**

For extraction of jackfruit seed starch mainly three different methods were used namely distilled water method, alkali method and enzyme as given below.

**1. Extraction of starch by using distilled Water Method**

The extraction of jackfruit seed starch by using distilled water involved adding 5g of jackfruit seed flour to 100ml of distilled water, soaking for 6 to 8 hours, and stirring constantly. The mixture was then filtered through a 212 mesh sieve, and the sediment was washed with distilled water. The filtrates were combined and precipitated overnight at 4°C. After discarding the supernatant, the crude starch was cleaned and dried at 40°C for 24 hours. The starch was ground and stored at room temperature. The optimum soaking time for maximum yield was determined to be 6 hours (Noor *et al.* 2014; Tulyathan *et al.* 2002).

**2. Extraction of starch by using Alkali Method**

Extraction of jackfruit seed starch was performed

**Table 2:** Composition of Jackfruit seed reported by various authors in the Literature

| Sl. No. | Parameter | Saha *et al.* (2022) | Swami *et al.* (2019) | Amadi *et al.* (2018) | Gupta *et al.* (2011) | Ranasinghe *et al.* (2019) | Banerjee and Datta (2015) |
|---|---|---|---|---|---|---|---|
| 1 | Moisture content % | 51.0-64.5 | 51.0-64.5 | 71.9 | 61.8 | — | 64.5 |
| 2 | Protein % | 0.4 | 6.6-7.04 | 10.1 | 11.9 | 13.50% | 6.6 |
| 3 | Fat % | 0.4 | 0.40-0.43 | 4.3 | 1.0 | 1.27% | 0.4 |
| 4 | Carbohydrate % | 25.8-38.4 | 25.8-38.4 | 7.9 | 26.2 | 79.34% | 25.8 |
| 5 | Crude Fiber % | 1.0-1.5 | 1.0-1.5 | 3.9 | — | 3.19% | 1.5 |
| 6 | Ash % | — | — | 0.9 | 0.2 | 2.70% | — |
| 7 | Starch % | — | — | — | — | 22% | — |
| 8 | Vitamin A(IU) | 10.0-17.0 | 10.0-17.0 | — | — | | — |
| 9 | Vitamin C (mg) | 11.0 | 11.0 | 0.11 | — | | — |
| 10 | Calcium (mg) | 50.0 | 50.0 | 40.0 | 29.5 | 3,087mg/kg | 50 |
| 12 | Potassium (mg) | 246.0 | 246.0 | 220.0 | 786.6 | 14,781mg/kg | 246 |
| 13 | Manganese (mg) | — | — | 9.5 | — | 1.12mg/kg | — |
| 14 | Magnesium (mg) | 54.0 | 54.0 | — | — | | 54 |
| 15 | Iron (mg) | 1.5 | 1.5 | 18.3 | — | 130.74mg/kg | 1.5 |
| 16 | Riboflavin (mg) | — | 0.11-0.3 | — | — | | — |
| 17 | Thiamine (mg) | — | 0.25 | — | — | | — |
| 18 | Phosphorous (mg) | 38.0-97.0 | 38.0-97.0 | — | — | | — |
| 19 | Zinc (mg) | — | — | 9.28 | 2.3 | | — |
| 20 | Sodium (mg) | | 63.2 | | | 60.66mg/kg | 63.2 |
| 21 | Copper (mg) | | | | | 10.4mg/kg | 0.19 |
| 22 | pH | | | | | 5.78 | — |
| 23 | Lactic acid | | | | | 1.12% | — |

using modified methods from Bobbio *et al.* (1978), Singh and Singh (2001), Dutta *et al.* (2011) and Luciano *et al.* (2017) i.e., Alkali method. A 5g sample of jackfruit seed flour was treated with different concentrations of NaOH (0.1%, 0.25%, and 0.5%) and soaked for 6-8 hours at room temperature, followed by constant stirring. The slurry was filtered through a 212 mesh sieve, washed with distilled water thrice, and the filtrates were precipitated overnight at 4°C. The supernatant was discarded, and the starch was cleaned with distilled water, dried at 40°C for 24 hours, and ground. The optimal extraction conditions identified were 0.5% NaOH and a soaking time of 6 hours, based on yield.

### 3. Extraction of starch by using enzyme

Extraction of starch from jackfruit seeds was performed using a modified method by Perez *et al.* (1993) and Singh and Singh (2001). Five grams of jackfruit seed flour were treated with varying concentrations of $\alpha$-amylase (0.1 g, 0.25 g, and 0.5 g) and soaked in 100 ml of water for 6 and 8 hours at room temperature, maintaining a pH of 6.0. The slurry was filtered through a 212 mesh stainless sieve, and the sediment was washed three times with distilled water. The combined filtrates were precipitated overnight at 4°C, and after discarding the supernatant, the crude starch was cleaned with distilled water. This process was repeated three times, and the starch cake was dried at 40°C for 24 hours before being ground and stored. The optimal conditions identified were 0.25 g of enzyme and a soaking time of 6 hours for the highest yield.

According to physico-chemical and functional properties analysis the distilled water method produced a greater yield, amylose content, and

**Table 3:** Physico-chemical and Functional Properties of Three varieties of Jackfruit Seed Starch extracted by using different methods (Noor *et al.* 2014)

| Sl. No. | Parameter | Extraction Methods | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Distilled water | | | Alkaline | | | Enzymatic | | |
| | | Gala Variety | Durasha variety | Khaja variety | Gala Variety | Durasha variety | Khaja variety | Gala Variety | Durasha variety | Khaja variety |
| 1 | Moisture content % | 9.56 ± 0.13 | 10.01 ± 0.71 | 10.44 ± 0.46 | 8.58 ± 0.82 | 8.43 ± 0.44 | 8.39 ± 0.36 | 12.20 ± 0.42 | 11.57 ± 0.48 | 11.91 ± 0.33 |
| 2 | Protein Content % | 3.47 ± 0.15 | 3.67 ± 0.18 | 3.41 ± 0.23 | 1.41 ± 0.09 | 1.26 ± 0.09 | 2.23 ± 0.15 | 1.28 ± 0.41 | 1.09 ± 0.05 | 1.18 ± 0.02 |
| 3 | Fat content % | 0.03 ± 0.01 | 0.04 ± 0.01 | 0.03 ± 0.002 | 0.02 ± 0.01 | 0.002 ± 0.02 | 0.03 ± 0.01 | 0.03 ± 0.01 | 0.02 ± 0.01 | 0.03 ± 0.01 |
| 4 | Ash content % | 0.04 ± 0.01 | 0.04 ± 0.01 | 0.03 ± 0.01 | 0.04 ± 0.01 | 0.004 ± 0.01 | 0.01 ± 0.01 | 0.45 ± 0.05 | 0.59 ± 0.04 | 0.56 ± 0.05 |
| 5 | Amylase % | 26.57 ± 0.13 | 30.61 ± 0.18 | 31.37 ± 0.9 | 25.14 ± 0.09 | 25.75 ± 0.18 | 25.49 ± 0.9 | 22.13 ± 0.14 | 22.17 ± 0.09 | 22.10 ± 0.14 |
| 6 | Total Starch % | 86.71 ± 1.79 | 83.83 ± 3.15 | 85.86 ± 1.84 | 83.15 ± 2.86 | 80.87 ± 2.73 | 79.35 ± 5.72 | 80.21 ± 1.59 | 73.46 ± 1.31 | 72.58 ± 1.34 |
| 7 | Purity % | 94.08 ± 1.70 | 92.98 ± 2.69 | 95.58 ± 0.92 | 97.72 ± 1.32 | 95.65 ± 2.75 | 94.80 ± 1.69 | 95.06 ± 1.58 | 93.18 ± 3.11 | 93.83 ± 3.22 |
| 8 | Yield % | 84.33 ± 0.39 | 83.62 ± 0.12 | 84.48 ± 0.26 | 58.75 ± 0.95 | 55.95 ± 0.85 | 57.34 ± 0.91 | 55.51 ± 0.23 | 50.69 ± 0.75 | 52.74 ± 1.23 |

swelling water capacity compared to the alkaline and enzymatic methods. Enzymatic method gave highest amount of water absorption index and water soluble index as compared to distilled water and alkaline method. Physico-chemical and functional properties analysis is given in Table 3. Also in the Table 4 (a) and Table 4(b) all the physico-chemical and functional properties of jackfruit seed starch which was extracted by different method given below. That gives the total information about how the methods affects its properties.

**Morphological Characteristics and functional properties of jackfruit seed starch**

**1. Morphological Characteristics of Jackfruit seed starch**

**1.1. Granular morphology and size distribution**

Scanning electron microscopy (SEM) shows that jackfruit seed starch granules have round and semi-oval or bell-shaped (Madruga *et al.* 2014; Rengsutthi and Charoenrein, 2011; Yazid *et al.* 2019). The granules usually have a surface that is smooth. However, some granules may have an inward curve that makes them look hollow, or they may have small, uneven cuts on the surface, depending on the cultivar. When viewed under polarized light, Jackfruit seed starch granules have a central Maltese cross, which shows that they have a well-organized semicrystalline structure. Amylose is more concentrated at the edge of the granule, while amylopectin is more concentrated in the core crystalline region (Zhang *et al.* 2021; Madruga *et al.* 2014; Wong *et al.* 2021).

Compared to potato and corn starch, jackfruit seed starch has a smaller range of size. According to the above mentioned Table 5, jackfruit seed starch has a smooth surface, and corn starch has a rough surface. Starch granule size is the most important factor in fried products that affect the oil absorption in fried food. Small granules often make a more even and dense matrix, which keeps oil from getting in (Zhang *et al.* 2024a). How starch granules "fill" the voids in a gluten network depends on their

**Table 4: (a)** Physico-chemical and Functional Properties of Jackfruit Seed Starch

| Method of starch extraction | Moisture % | Protein % | Lipid % | Ash % | Fiber % | Amylase content % | Amylopectin % | Starch % | ph | Purity % | Yield % | Crystaline structure | Particle size (µm) | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Distilled water | 9.56 ± 0.13 | 3.47 ± 0.15 | 0.03 ± 0.01 | 0.04 ± 0.01 | — 26.57± | 0.13 — | 86.71 ± 1.79 | — 94.08± | 1.70 | 84.33 ± | 0.39 | — | — | Noor *et al.* (2014) |
| | 7.94±0.01% | — | — | 0.58 ± 0.05% | — | — | — | — | 4.97 ± 0.59 | — | — | — | 7.25±3.33 | **Hundekari (2018) |
| Alkaline | 8.58 ± 0.82 | 1.41 ± 0.09 | 0.02 ± 0.01 | 0.04 ± 0.01 | — | 25.14 ± 0.09 | — | 83.15 ± 2.86 | — | 97.72 ± 1.32 | 58.75 ± 0.95 | — | — | Noor *et al.* (2014) |
| Enzymatic | 12.20 ± 0.42 | 1.28 ± 0.41 | 0.03 ± 0.01 | 0.45 ± 0.05 | — | 22.13 ± 0.14 | — | 80.21 ± 1.59 | — | 95.06 ± 1.58 | 55.51 ± 0.23 | — | — | Noor *et al.* (2014) |
| Separation of starch granules according to particle size using glycerol-assisted centrifugal sedimentation | — | — | — | — | — | 24.35–28.29 | — | 87.90 ± 0.23 | — | — | — | A-type | 4.0–16.0 | *Chacon *et al.* (2024) |
| Alkaline | 9.59-12 | 0.09 | 0.03 | 0.04 | 0.19 | 20-32.14 | 80 | — | — | — | — | — | — | Rengsutthi and Charoenrein, (2011); Kushwaha, *et al.* (2023b); Akter and Haque (2019); Phukan, *et al.* (2018) |

**Table 4: (b)** Physico-chemical and Functional Properties of Jackfruit Seed Starch

| Granule Shape | Peak temp. at Gelatinization (°C) | Gelatinization enthalpy ΔHgel [J g$^{-1}$] | Pasting Temp. (°C) | Peak Viscosity m Pa s | Digestion condition (37°C) | Rapidly digestible starch (RDS, %) | Slow Digestible starch (SDS, %) | Resistant Starch | Bulk Density | Water absorption capacity | Swelling Vol. | Swelling Power | Solubility | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Spherical, oval, round, trigonal, and tetragonal | 78.3–87.0 | 6.2–16.8 | 80.0–91.4 | 2210.0–3483.0 | Porcine pancreatin (0.15 g mL$^{-1}$) and amyloglucosidase (260 U mL$^{-1}$) | 9.54 ± 0.17 | 13.68 ± 1.92 | 76.38 ± 2.1 | — | — | — | — | — | *Chacon *et al.* (2024) |
| | 74.00 ± 3.54 °C | — | — | — | — | — | — | — | 0.504 ± 0.05 g/cc | 1.184 ± 0.08 g/g | 1.53 ± 0.22 ml, | 8.21 ± 0.73 g/g | 1.712 ± 0.50% | **Hundekari (2018) |

***Note:*** ** and ** shows the similar method of extraction of starch from jackfruit seed.*

surface shape. While microscopic, high-surface-area granules might damage the matrix, smooth, moderately-sized granules are very mobile. Poor dough quality and low tensile strength are caused by thick protein strands and weak cross-linking caused by improper granule size (Hu *et al.* 2025). Small granules, which have a higher surface-to-volume ratio, usually have more Rapidly Digestible Starch (RDS) than larger granules from the same plant (Ma *et al.* 2022). Reducing a particular surface area can improve [Resistant Starch's] resistance to enzymatic hydrolysis by preventing excessive interaction with enzymes (Wang and Tong, 2024). Large size starch granule increases the pasting viscosity and thermal resistance as compared to small size granules (Zhao *et al.* 2015).

### 1.2. Crystalline Structure

The crystalline structure occurred in Jackfruit seed starch was A-type, which is mostly found in cereal crops like corn, wheat etc. (Rengsutthi and Charoenrein, 2011; Madruga *et al.* 2014). Mostly the crystalline structures for the intact granules according to diffraction pattern named as A-, B- and C- type. The packing density of amylopectin double helices determines X-ray diffraction (XRD) patterns. A-type polymorph shows the compact packing and less water between the double helix structure. B-type polymorph shows the open or hexagonal packing style surrounding to the central water column. C-type polymorph have a mixed i.e. both A- and B-type packing style. A-type polymorph shows strong peak at 15°, 17°, 18° and 23°, for B-type it shows peak at 5.6°, 17°, 22° and 24°. C-type polymorph shows peak at 5.6° and 17°. A-type polymorph is inherently more resistant to enzyme penetration due to their tight molecular structure, which can aid in the development of meals with a lower glycemic response. Due to the high density these type starch is mostly used as thickener, with thermal stability (Ouyang *et al.* 2024).

### 1.3. Amylose and Amylopectin Content

In comparison to many commercial kinds of starch, jackfruit seed starch (JSS) is categorized as a high-amylose starch. The main factor influencing its distinct cooking stability and nutritional composition is the ratio of its linear amylose to branched amylopectin molecules. The typical range of amylose content is 22.10% to 38.34%. Depending on the cultivar and extraction technique, some studies claim levels as high as 44–50% (Zhang *et al.* 2021). Compared to rice starch (~17%) and potato starch (~24–27%), its amylose levels are higher (Wong *et al.* 2021). While amylose supplies the structural network for solid gels and long-term stability, amylopectin is responsible for the first thickening and water absorption (Kumar and Khatkar, 2017). At lower temperatures, amylopectin causes starch granules to enlarge and become more viscous. Usually, amylose prevents swelling by strengthening the starch granule's interior structure. Elevated quantities of amylose might hinder the process of gelatinization, necessitating higher temperatures and greater energy to break up the crystalline areas (Cornejo-Ramirez *et al.* 2018; Juhasz and Salgo, 2008; Kumar and Khatkar, 2017). The main gelling agent is amylose. Its linear chains align and create strong hydrogen bonds when

**Table 5:** Granular Size comparison of jackfruit seed starch with other starches

| Starch Source | Typical Granule size | Shape Characteristics | References |
|---|---|---|---|
| Jackfruit Seed | ~ 7.0-11.0 μm | Round to bell shaped, smooth | Zhang *et al.* (2021); Madruga *et al.* (2014). |
| Rice | ~ 3.1-10.2 μm | Small, polygonal, and irregular, Angular | Wong *et al.* (2021) |
| Mung Bean | ~ 22.1 μm | Oval-shaped; larger than JSS, smooth | Phrukwiwattanakul *et al.* (2014) |
| Potato | ~ 30.5-43.4 μm | Large, oval, or elongated; smooth | Wong *et al.* (2021) |
| Corn | ~ 12.77 – 13.64 μm | Oval to Polyhedral, rough and porous | Sandhu *et al.* (2004) |

it cools, forming a solid, opaque three-dimensional network. Stiff, brittle gels are produced by high-amylose starches. Amylopectin-rich starches have sticky, stretchy, and soft textures (like glutinous rice). It frequently forms translucent, flexible sols instead of firm gels because it lacks the long linear chains required for a stiff network (Boonkor *et al.* 2022; Li *et al.* 2016). The initial firming of bread and the development of resistant starch are caused by the quick retrogradation of amylose (within hours or days) (Yu *et al.* 2009). Through the recrystallization of its side chains, amylopectin retrogrades far more slowly (over days or weeks). Long-term staling in starchy foods is mostly caused by this process (Wang *et al.* 2024).

**3.2 Functional properties of jackfruit seed starch**

**2.1. Water Absorption Capacity (WAC)**

Water absorption capacity of jackfruit seed starch was 115.00 gm of water / 100gm of starch at 27 °C and it changes according to the cultivar. Jackfruit seed starch contains large quantity of free hydroxyl (-OH) groups, these groups are acting as active site to form strong hydrogen bond with water molecules causes high water absorption. The amylose content of JSS is considerable, usually ranging from 25% to 45%. Since amylose is primarily found in amorphous regions—where water molecules can pass through more readily than in dense crystalline regions—higher amylose levels are positively correlated with WAC (Karadbhajne and Sawant, 2014; Kushwaha *et al.* 2023a; Zhang *et al.* 2024b).

**2.2. Swelling power and Solubility**

As mentioned in Table 4, the swelling power and solubility of jackfruit seed starch were 8.21±0.73 g/g and 1.712±0.50% respectively (Hundekari, 2018). The Jackfruit seed starch has lower swelling power and solubility because it contains high percentage of amylose. Strong hydrogen connections created by the linear amylose chains strengthen the granule structure and stop it from absorbing too much water (Madruga *et al.* 2014). JSS has excellent heat-resistant structural integrity, needing temperatures over 75 °C before noticeable swelling happens. Its granules have minimal breakdown viscosity when heated, suggesting that they are quite resilient to mechanical and thermal shear. Because of this stability, the granules remain intact for a longer period of time, avoiding rupture and the release of soluble starch components that would improve solubility (Barbosa *et al.* 2023).

**2.3. Gelation behavior**

Strong, firm and elastic gels can be formed from jackfruit seed starch. Higher chewiness, hardness, and elastic modulus (G′) gels are the result. in contrast to the starches in potatoes or rice (Wong *et al.* 2021).

**2.4. Retrogradation Tendancy**

This starch has a high potential to retrograde, which causes gels to solidify quickly over time. Rapid recrystallization into a rigid network is made possible by an abundance of linear chains (Wong *et al.* 2021). Setback viscosity in pasting property tests quantifies the rise in viscosity when a starch paste cools, which is a clear sign of retrogradation. Jackfruit seed starch has high setback value it means defined as the degree of re-association between the starch molecules involving amylose (Rengsutthi and Charoenrein, 2011).

**Modification of Jackfruit Seed Starch**

Now days in various industries starch is used for its various applications like in food and non-food industry. To improves the properties of starch various modification techniques were used includes physical modification, chemical modification, enzymatic modification and genetic modification technique (Fatima *et al.* 2024). The goal of these changes is to bring about desired changes in the starch structure, which will make its behavior predictable and under control. Thus, either glucosidic bond cleavage (acid modification to dextrins) or the formation of new functional groups (carbonyl group formation during oxidation), the replacement of free available hydroxyl groups (etherification or esterification), or the bridging of molecular chains by cross-linking reactions result in the modified starch derivatives (Tharanathan, 2005). Table 6 shows the different modification methods used while modification of Jackfruit seed starch.

**1. Physical Modification**

Since physical modification doesn't include chemicals or biological agents, it is easy, affordable, and safe. Classification of the physical modification is done by using different criteria i.e., based on structural integrity of starch after modification; thermal and non-thermal modification. Thermal modification involves extrusion, annealing, heat moisture treatment, hydrothermal treatment. Non-thermal modification involves microwave and ultrasonication (Ashogbon, 2018). Heat moisture treatment and annealing are the hydrothermal treatment. Enhancing the degree of starch crystallinity, arranging starch chains in crystalline and amorphous layers, and strengthening the crystalline form of granules are the goals of hydrothermal treatment (Fatima *et al.* 2024). In the heat moisture treatment starch granules are heated to temperatures higher than the gelatinization temperature, with a moisture level inadequate to gelatinize the starch, and then subjected to a predetermined amount of time, preserving the granular integrity. Temperature range was 84-140°C, moisture content range was 10-35% and time of exposure was 1h to 16 h (Fonseca *et al.* 2021). Through a hydrothermal process called annealing, starch with an excessive (~70%, v/v) or intermediate (~40%, v/v) water content is heated over the glass transition temperature and below the starch's gelatinization temperature for a duration that can range from minutes to days (Punia, 2020). A thermomechanical process called extrusion has the ability to disrupt the bonds in starch, which causes it to melt, degrade, and gelatinize (Ye *et al.* 2018). By depolymerizing the starch granules through high shear mechanisms, extrusion raises the resistant starch levels. In turn, this straightens chains that are more prone to degenerate into retrograded amylose (Fatima *et al.* 2024).

When heating starch in a microwave, electromagnetic waves with frequencies between 300 GHz and 300 MHz are applied. Polar materials can align themselves with an electric field by absorbing microwave radiation, such as starch. The starch modification by microwave treatment is divided into four stages i.e., the first step involves the water molecule's dielectric relaxation phenomena, which causes the starch to heat up initially. The temperature rises quickly after this, and the interior of the starch granule loses moisture as a result. The granules expand from the center due to the high pressure that the moisture loss allegedly creates inside them. The breakdown of the starch granules is evident in the last step (Oyeyinka *et al.* 2021). One physical alteration technique that makes use of frequencies higher than the human hearing threshold is ultrasound. The multi-scale structure of starch will be altered in the starch-water system by the physical effects (hole effect, mechanical effect, etc.) produced by ultrasonic treatment, which will also cause high temperatures, severe shear forces, and free radicals in the surrounding area. The morphology and ultrastructure of polymers are altered when cracks and holes form on the surface of starch particles, altering the structure and characteristics of starch (Wang *et al.* 2023).

**2. Chemical Modification:**

Chemical modification is conducted to alter the molecular structure of native starch by adding or replacing its functional groups in order to stop enzymatic digestion. Three primary processes—cross-linking, esterification and etherification, and acid treatment—are used to create resistant starch using the chemical modification (Dupuis *et al.* 2014).

Etherification of starch involves first alkalization then the etherification. A more reactive "Starch-Alkoxide" intermediate is produced when the starch and sodium hydroxide (NaOH) react.

$$Starch - OH + NaOH \rightarrow Starch - O^{-}\,Na^{+} + H_2O$$

The following reaction takes place during the etherification process: a stable ether bond is formed, the starch-alkoxide attacks sodium monochloroacetate (SMCA) as a nucleophile, and the chlorine atom is replaced.

$$Starch - O - Na^{+} + Cl - CH_2\ COONa \rightarrow Starch - O - CH_2\ COONa + NaCl$$

Here the hydroxyl group of the starch is substituted by the carboxymethyl group. Oxygen from the starch forms the stable ether bond between the starch and carboxymethyl group. Due to the carboxymethylation, starch can be soluble in cold water also the swelling power and paste clarity is inceased (Tharanathan, 2005; Kittipongpatana and Kittipongpatana, 2011).

$$Starch - OH + C_3H_6O \xrightarrow{NaOH + N_2SO_4} Starch - O - CH_2 - CH(OH) - CH_3$$

Also for production of hydroxypropyl modified starch, it is reacted with propylene oxide. The chemical reaction for the hydroxypropyl starch is given below (Singh *et al.* 2007).

Phosphate cross linked jackfruit starch modification is conducted previously (Kittipongpatana, and Kittipongpatana, 2011). The technique of cross link modification involves treating the native starch with a variety of chemicals reagents including citryl, phosphate, acetyl, hydroxypropyl, and octenylsuccinyl groups, respectively. These reagents substitute the hydroxyl group of starch o form the ether or ester linkage. Phosphate alteration has enhanced properties like increased texture and viscosity, resilience to low pH, high shear, and heat stability (Kavlani *et al.* 2012). Starch is treated with sodium tri-metaphosphate the complete reaction is given below (Singh *et al.* 2007).

$$2(Starch) + Na_3\ P_3\ O_9 + 2NaOH \rightarrow \underbrace{Starch - O - PO_2}_{\text{Cross Linked starch}}$$

$$Na - O - Starch + \underbrace{Na_2P_2O_4}_{\text{Sodium pyrophosphate}} + H_2O$$

Modification of starch by using acid includes mainly using HCl and Malic Acid. In the Modification of starch by using HCl involves the hydrolysis of glycosidic bond. Reaction between the HCl and starch is given below:

$$Starch_n + H_2O \xrightarrow{H^+(From\ HCl)} (Starch)_{n-X} + (Glucose)_X$$

Glycosidic linkages are hydrolyzed by hydrochloric acid, which serves as a catalyst. By breaking down long chains of amylose and amylopectin into smaller pieces known as dextrins, it makes the starch paste more soluble and less viscous. Hydrochloric acid $H^+$ ion protonates the glycosidic $O^-$ion. Following this, a water molecule is added across the bond, causing the cleavage of the $\alpha$1-4 glycosidic bond and $\alpha$1-6 glycosidic bond connections (Halim *et al.* 2024).

Malic acid is a dicarboxylic acid (HOOC-CH(OH)-$CH_2$-COOH). It chemically connects to the starch molecules through esterification, which is different from HCl. It can also work as a cross-linking agent because it possesses more than one functional group. This means it can connect two distinct starch chains. The chemical reaction for the modification of starch is given below:

$$Starch - OH + R - COOH\ (Malic\ Acid) \xrightarrow{\Delta} Starch - O - CO - R + H_2O$$

The carboxyl groups (-COOH) of the malic acid react with the hydroxyl groups (-OH) on the glucose units of the starch. An ester bond is created and a water molecule is removed by this condensation reaction. Malic acid can form a cross-linked network by reacting with two distinct hydroxyl groups (on the same or different starch chains) since it contains two carboxyl groups. It reduces solubility in comparison to starch treated with HCl, increased resistant starch content, and enhanced thermal stability (Singan and Liew, 2016).

Also the modification of starch is done by oxidation of starch by using sodium hypochlorite (NaOCl) as the reaction below. At first the dissociation of sodium hypochlorite is occurred which releases the hypochlorite ions as given in reaction below:

$$NaOCl \rightarrow Na^{+} + OCl^{-}$$

***Dissociation***

Then the hypochlorite ions reacts with hydroxyl group (-OH) to remove the hydrogen to form an aldehyde (CHO).

$$Starch - CH_2\,OH + OCl^- \rightarrow Strach - CHO + Cl^- + H_2O$$

The extremely reactive aldehyde group is further oxidized into a carboxyl group (-COOH) when additional hypochlorite is present. This occurs as a sodium carboxylate salt (-COONa) under the alkaline conditions (pH 8–10) that are used.

$$Starch - CHO + OCl^- + NaOH \rightarrow Starch - COONa + Cl^- + H_2O$$

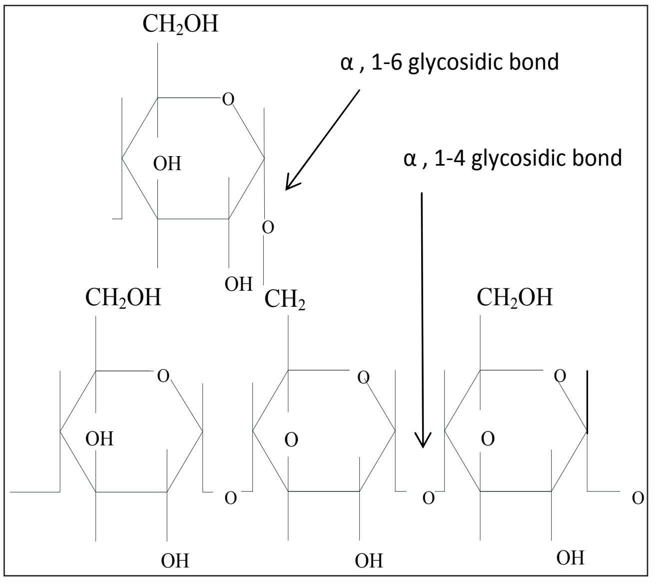
The complete reaction for the modification of starch is;

$$Starch - CH_2 - OH + 2NaOCl \rightarrow Starch - COONa + NaCl + HCl + H_2O$$

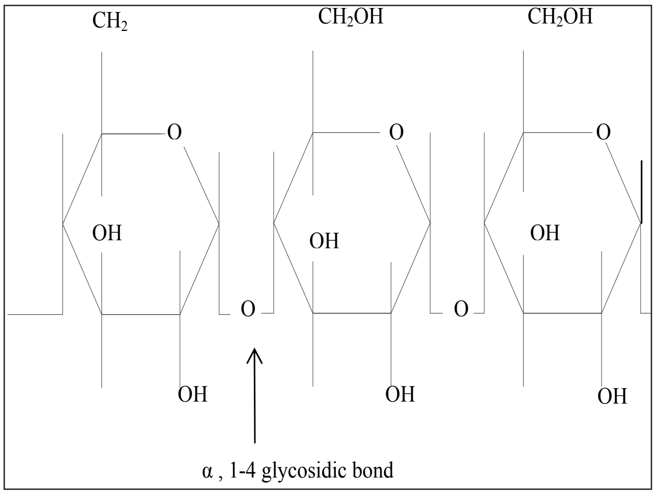
This process replaces hydroxyl groups with carbonyl and carboxyl groups (Sukhija *et al.* 2016; Kuakpetoon and Wang, 2006).

**3. Enzymatic Modification**

Starch which is a carbohydrate mainly composed of amylose and amylopectin. Amylose contains $\alpha$-1-4 glycosidic linkage and amylopectin contains $\alpha$-1-4 and $\alpha$-1-6 glycosidic linkage. Regardless of its origins and sources, starch will be less useful in its natural state.(Yazid *et al.* 2018). Therefor modification of the starch is done by various means and enzymatic modification is from that. The enzymatic modification of starch involves cutting of $\alpha$-1-4 glycosidic linkage and $\alpha$-1-4 and $\alpha$-1-6 glycosidic linkage. There are different kinds of enzymes are used for debranching of the starch structure that involves enzymes like $\alpha$ amylase, βamylase, glucosidase, glucoamylase, isoamylase and pullulanase etc. Each enzyme have different properties. Enzymes hydrolyze starch's glycosidic linkages to produce polymeric or oligomeric molecules. These enzymes include exo-acting enzymes that cleave glycosidic bonds at the nonreducing ends, producing monomeric or oligomeric molecules, and endo-acting $\alpha$-amylase, which breaks $\alpha$-1,4 bonds in amylose and amylopectin. In particular, pullulanase, a debranching enzyme, breaks $\alpha$-1,6 glycosidic linkages, whereas β-amylase targets $\alpha$-1,4 bonds in amylose and amylopectin (Choton *et al.* 2024; Fatima *et al.* 2024; Yazid *et al.* 2018).




**(a)** Structure of Amylopectin
(El-Fallal *et al.* 2012)




**(b)** Structure of amylose
(El-Fallal *et al.* 2012)

**Fig. 2: (a)** Structure of amylopectin **(b)** structure of amylose present in Jackfruit seed starch

**Table 6:** Different modification methods used while modification of Jackfruit seed starch

| Sl. No. | Modification method | Technique | Principle | Effect of Modification | Reference |
|---|---|---|---|---|---|
| 1 | Physical Modification | Extrusion | Shear forces, low screw speed (20–30 rpm), barrel temperature (90–110 ◦C), and pressure (120 MPa) | After IECT, JFSS's in vitro digestibility was considerably increased because, according to main component analysis, the starch supramolecular structure was destroyed. Also the JFSS's crystalline structure changed from being A-type to V-type. | Zhang *et al.* (2021) |
| | | Hydrothermal treatment | For 20, 30, or 60 minutes, the starch will partially gelatinize at a temperature of 70 °C. | Water holding capacity is high in partially gelatinized Jackfruit seed starch | Tran *et al.* (2015) |
| | | Annealing | The starch was heated at 45, 50, 55, and 60 °C for 72 hours in order to perform single-stage annealing. Double-stage annealing required a second initial heating phase that lasted the same amount of time but was 10 °C lower than the previously specified temperature. | Jackfruit seed starch's crystalline order was observed to enhance after single-stage annealing. | Bhattacharjya *et al.* (2015) |
| | | Heat Moisture treatment | Jackfruit seed starch samples with 20,25,30 and 35% moisture content was in a hermetically sealed stainless steel container and heated in a hot-air oven set at 80, 90, 100, 110, and 120°C for 6, 12, and 16 hours. Then the samples were dried in Hot Air Oven for about 40°C for 48 h. | Increase in Resistant starch content. | Kittipongpatana and Kittipongpatana (2015) |
| | | Microwave treatment | Using an acid solution and 3 watts of power, starch hydrolysis was carried out for 2.5 minutes at 35°C. | Higher water absorption capacity, amylose content increases and solubility increases. It gives higher swelling power, | Karadbhajne, and Sawant (2014) |
| | | Ultrasonication | Ultrasonic probe with frequency of 19.5–20.5 kHz and a power of 170 Watt used at 30 °C for 30 min (3 s ON followed by 5 s OFF) | Ultrasonic treatment reduced the oil absorption capacity and swelling power. | Banyal *et al.* (2023) |

**(Cont…)**

| | | | | | |
|---|---|---|---|---|---|
| 2 | Chemical Modification | Carboxymethyl jackfruit starches | Different alcoholic solvents were used methanol (m-CMJF), 1-propanol (n-CMJF), 2-propanol (i-CMJF) | High capacity to absorb water. Granules are clearly fractured. low crystallinity. high stability during heat curing and high apparent viscosity. | Kittipongpatana, and Kittipongpatana (2011) |
| | | Hydroxypropyl starch | 1g/L NaOH, $Na_2SO_4$ and reaction with propylene oxide for 40 °C for 24 h. pH is adjusted by using 2 mol/L HCl. | At room temperature, insoluble or only slightly soluble in water. minimal crystallinity. low temperature for gelatinization. | |
| | | Phosphate cross-linked jackfruit starch | Sodium sulfate and sodium trimetaphosphate and pH adjusted by aqueous sodium hydroxide. Slurry stirred for about 2 h at 50°C. | Low crystallinity and low solubility. | |
| | | Acid -alcohol Modification | Short term- hydrochloric acid and 70% alcohol (1:2 v/v)<br>Long term – 1 M hydrochloric acid in absolute alcohol | Loss in crystallinity occurs in long term treatment as compared to short term treatment. The treated starch can be utilized as filling for confectionery. | Dutta *et al.* (2011) |
| | | Oxidation | Sodium hypochloride with 1%, 2%, 3%, 4% and 5% conc. Were used. Maintained the pH by 1M $H_2SO_4$ | During low-temperature storage, oxidation improved the starch gel's whiteness, paste clarity, and stability. Better stability and water retention during refrigeration were indicated by the oxidized starch's decreased syneresis. | Naknaen *et al.* (2017) |
| | | Acid Modification | 0.1 M HCL<br>0.2 M HCL and 0.3 M HCL ; 0.5 M Malic Acid 1 M Malic Acid 1.5 M Malic Acid | For the HCL treated starch based film moisture content, thickness and opacity is low as compared to Malic acid. The solubility is more in HCL treated starch based film. | Kushwaha *et al.* (2025) |
| | | Etherification with Propylene Oxide | Propylene Oxide was used in amount of 10ml, 20ml, 30ml, 40ml and 50 ml.<br>Starch suspension was neutralized by diluted 0.1M HCL solution. | Gelatinization temperature and crystallinity decreased. Increase in the whiteness, swelling power, solubility, paste clarity and stability of the starch gel during low temperature storage; | Naknaen (2014) |
| 3 | Enzymatic Modification | β amylase modification | 8% of β-amylase (91,500 U/g), pH 5.5, temperature 50–60 ◦C | Transparent, yellow colored viscous maltose syrup was obtain. | Zhang *et al.* (2011) |

### 5. Recent application of jackfruit seed starch

#### 1. Food Industry

In the backing industry jackfruit seed starch was used in the development of cupcake, it can replace 15% wheat flour (Khang *et al.* 2020). Jackfruit seed starch was used in different soup mixes as a thickener (Sargar and Swami, 2025). Jackfruit seed starch was also utilized for coating on wrapping paper for active food packaging (Kumar *et al.* 2026). Santhosh and Sarkar (2022) composite film was prepared using jackfruit seed starch, tamarind kernel xyloglucan and zinc oxide nanoparticle. The composite film was applied to tomato fruit, which improves shelf life and slows down quality loss. When JSS and xyloglucan are combined, the hydrophilic characteristics of the composite films are decreased while the material strength is increased. Also jackfruit seed starch is useful in building insulation.

#### 2. Pharmaceutical Industry

Also according to research conducted by Zhang *et al.* (2025) shows that the use of jackfruit seed resistant starch loser the high level of fat in blood by changing the bacteria living in the gut. This starch specifically help to reduce the high levels of lipids in the blood such as triglycerides and bad i.e. low density lipoprotein cholesterol and increases the good i.e. high density lipoprotein cholesterol. Jackfruit seed starch was used for formulation of microencapsulated anthocyanin-rich powder as an encapsulation material. The study has proven jackfruit seed starch (JSS) is an effective, natural material for protecting and delivering sensitive health-promoting ingredients in food products (Patel *et al.* 2020). Jackfruit seed starch is natural and promising ingredient used to prepare composite beads that act as effective sustained-release drug delivery systems. These jackfruit seed starch based beads, when combined with other biopolymers, provide controlled long term release of medicine and have demonstrated significant in vivo, blood-sugar-lowering effect (Nayak *et al.* 2021).

#### 3. Other Industry

Jackfruit seed starch was used in various industries in the recent year; for example, for the fabrication of packaging material, jackfruit seed starch was used. Nguyen *et al.* (2025) used jackfruit seed starch for the development of intelligent film with the incorporation of polyvinyl alcohol and the use of sweet potato peel anthocyanin as an indicator. It was used to detect the shrimp's freshness through change in the color. Polylactic acid is also used for the reinforcement of jackfruit seed starch based degradable plastic. The starch from jackfruit seeds combined with PLA-reinforced plastic exhibited superior thermal stability. The material swelled less with PLA and more with starch. Plastics made from jackfruit seed starch and reinforced with PLA broke down in 52–56 days, satisfying the ASTM 6400 requirement (Dewi *et al.* 2025). Kushwaha *et al.* (2025) used jackfruit seed starch for the development of biofilm using native and acid-modified jackfruit seed starch. Where the native jackfruit seed starch was modified by the application of HCl and malic acid. When compared to native starch biofilms, the malic acid alteration exhibited a wide range of film thickness variation, which resulted in more significant changes in solubility and opacity. According to Roy and Zhou (2026) had developed chemical free composite from banana and jackfruit seed starch, which are fully biodegradable. The banana stem produces fibrous lignocellulosic network while jackfruit seed starch used as binding matrix. Jackfruit seed starch-beeswax-glycerol-Pumelo peel extract solution was prepared and coated on wrapping paper. The solution prepared for coating having good barrier, mechanical and antioxidant properties which is suitable for preserving food products. Also the jackfruit seed starch is recent years used for treating the sevage as biocoagulant (Khuswah *et al.* 2025).

## CONCLUSION

This review paper provides a detailed evaluation of the potential of jackfruit *(Artocarpus heterophyllus)* seed starch as a sustainable, high potential alternative to the conventional commercial starches. Jackfruit seeds, a huge byproduct of agro-industrial waste, are a great vehicle for circular bioeconomy principles. Processing these into starch can solve environmental pollution and seasonal waste disposal problems and provide starch source that is economically competitive and does not threaten global food security. Jackfruit seed starch shows some interesting structural properties such as high amylose content, small granule size, high thermal stability and unique A-type crystalline structure. High-purity starches are obtained using advanced conventional and green extraction strategies such as ultrasonication and enzyme assisted methods. Moreover, physical, chemical and dual modifications are effective in tailoring jackfruit seed starch to overcome natural limitations such as high retrogradation and poor freeze-thaw stability. Such excellent properties open very versatile ways of its use.

However, moving jackfruit seed starch from academic research to industrial-scale application requires overcoming clear operational hurdles. Future research must prioritize solving the seasonal availability of jackfruits, standardizing low-cost industrial extraction process and validating the health benefits of jackfruit seed starch through targeted *in-vivo* clinical studies. Additionally, exploring nano-starch modification and composite material blending will unlock high-performance application in intelligent packaging and industrial engineering. Ultimately, commercializing jackfruit seed starch bridges the gap between waste valorization and material science, offering global industries a highly functional, sustainable and eco-friendly biopolymer.

## GENERATIVE AI DECLARATION

The author(s) confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript, and no images were manipulated using AI. The authors developed and verified all scientific content, data analysis, interpretation of results, and conclusions. The authors take full responsibility for the accuracy, integrity, and originality of the work presented, and no AI tool was listed as an author.

## REFERENCES


Akter, F. and Haque, M.A. 2019. Jackfruit waste: A promising source of food and feed. *Annals of Bangladesh Agriculture*, **23**(1): 91-102.

Amadi, J.A., Ihemeje, A. and Afam-Anene, O.C. 2018. Nutrient and phytochemical composition of jackfruit (*Artocarpus heterophyllus*) pulp, seeds and leaves. *International Journal of Innovative Food, Nutrition and Sustainable Agriculture*, **6**(3): 27-32.

Apoorva, M.S. and Kundlas, K. 2024. Negative impacts of intensive agricultural practices on environment and ecosystem: A review. *International Journal of Research in Agronomy*, **7**(12): 285-289.

Ashogbon, A.O. 2018. Current research addressing physical modification of starch from various botanical sources. *Global Nutrition and Dietetics,* **1**(1):1-7.

Banerjee, S. and Datta, S. 2015. Effect of dry heat treated jackfruit seed powder on growth of experimental animals. *IOSR Journal of Pharmacy and Biological Sciences*, **10**: 42-46.

Banyal, V.S., Shukla, A.K., Kumari, A., Kumar, A., Khatak, A., Luthra, A., Sunil and Kumar, M. 2023. Effect of modification on quality parameters of jackfruit (*Atrocarpus heterophyllus*) seed starch to valorize its food potential and *in-silico* investigation of the pharmacological compound against salmonellosis. *Waste and Biomass Valorization*, **14**(5): 1597-1610.

Barbosa, M.C., Silva, G.L., Viana, E.B.M., Bonomo, R.C.F., Rodrigues, L.B. and Veloso, C.M. 2023. Effect of protein addition in properties of gels produced with jackfruit (*Artocarpus integrifolia*) seed starch: rheological and texture properties. *Journal of Food Science and Technology,* **60**(12): 2916-2926.

Bhattacharjya, B., Dutta, H., Patwari, K. and Mahanta, C.L. 2015. Properties of annealed jackfruit (*Artocarpus heterophyllus* Lam.) seed starch. *Acta Alimentaria*, **44**(4): 501-510.

Bobbio, F.O., El-Dash, A.A., Bobbio, P.A. and Rodrigues, L.R. 1978. Isolation and characterization of the physico-chemical properties of the starch of jackfruit seeds (*Artocarpus heterorphyllus*). *Cereal Chemistry*, **55**: 505-11.

Boonkor, P., Sagis, L.M. and Lumdubwong, N. 2022. Pasting and rheological properties of starch paste/gels in a sugar-acid system. *Foods*, **11**(24): 4060(1-21).

Brahma, R. and Ray, S. 2023. Finding out various potentials and possibilities of jackfruit seed and its usage in the industry: a review. *Food Production, Processing and Nutrition*, **5**(1): 55.

Chacon, W.D.C., Gaviria, Y.A.R., de Melo, A.P.Z., Verruck, S., Monteiro, A.R. and Valencia, G.A. 2024. Physico-chemical properties and potential food applications of starches isolated from unconventional seeds: A review. *Starch-Stärke*, **76**(1-2): 2200228.

Chikkanna, G.S. 2021. Technical facts on the current scenario and future potential of jackfruit processing. *Research Biotica,* **3**(2): 94-106.

Choton, S., Bandral, J.D., Singh, J., Bhat, A., Sood, M., Gupta, N., Reshi, M. and Kaur, D. 2024. Enzymatic modification of starch: A review. *Saudi J. Med. Pharm. Sci.*, **10**: 1-8.

Cornejo-Ramirez, Y.I., Martínez-Cruz, O., Del Toro-Sanchez, C.L., Wong-Corral, F.J., Borboa-Flores, J. and Cinco-Moroyoqui, F.J. 2018. The structural characteristics of starches and their functional properties. *CyTA-Journal of Food*, **16**(1): 1003-1017.

Department of Agriculture and Farmer Welfare, 2024-25. https://agriwelfare.gov.in/en/Agriculture Estimates.

Deshmukh, P.S. and Swami, S.B. 2022. Moisture Dependent Physical Properties of Jackfruit Seed. *Int. J. Food Ferment. Technol.,* **12**(02): 97-106.

Dewi, R., Sylvia, N. and Riza, M. 2025. Effect of Polylactic Acid (PLA) as Reinforcement for Jackfruit Seed Starch-Based Degradable Plastic. *Engineering Proceedings*, **84**(1): 14.

Dhani, S., Ngobese, N.Z., Sharma, S. and Jaiswal, A.K. 2025. A comprehensive review on nutritional composition, health benefits, and industrial applications of Jackfruit Seeds. *Journal of Agriculture and Food Research*, **19**: 101692.

Dupuis, J.H., Liu, Q. and Yada, R.Y. 2014. Methodologies for increasing the resistant starch content of food starches: A review. *Comprehensive Reviews in Food Science and Food Safety*, **13**(6): 1219-1234.

Dutta, H., Paul, S.K., Kalita, D. and Mahanta, C.L. 2011. Effect of acid concentration and treatment time on acid–alcohol modified jackfruit seed starch properties. *Food Chemistry*, **128**(2): 284-291.

El-Fallal, A., Dobara, M.A., El-Sayed, A. and Omar, N. 2012. Starch and microbial a-amylases: from concepts to biotechnological applications. In Chuan-Fa Chang (Ed.) *Carbohydrates—comprehensive studies on glycobiology and glycotechnology*, pp.459-488. IntechOpen.

Fatima, S., Khan, M.R., Ahmad, I. and Sadiq, M.B. 2024. Recent advances in modified starch based biodegradable food packaging: A review. *Heliyon*, **10**(6): 27453.

Fonseca, L.M., El Halal, S.L.M., Dias, A.R.G. and da Rosa Zavareze, E. 2021. Physical modification of starch by heat-moisture treatment and annealing and their applications: A review. *Carbohydrate Polymers*, **274**: 118665.

Globe Newswire. Available online: https://www.globenewswire.com/en/news-release/2023/02/28/2617539/28124/en/Starch-Global-Market-to-Reach-199-8-Million-Metric-Tons-by-2030-Use-of-Starch-as-a-Fat-Replacer-Drives-Growth.html (accessed on 20 May 2026).

Gupta, D., Mann, S., Sood, A. and Gupta, R.K. 2011. Phytochemical, nutritional and antioxidant activity evaluation of seeds of jackfruit (*Artocarpous heterolphyllus* Lam.). *International Journal of Pharma and Bio Sciences*, **2**(4): 336-345.

Halim, A., Torley, P.J., Farahnaky, A. and Majzoobi, M. 2024. Investigating the Effects of Acid Hydrolysis on Physico-chemical Properties of Quinoa and Faba Bean Starches as Compared to Cassava Starch. *Foods,* **13**(23): 3885.

Hu, X., Xu, T., Bu, J., Cheng, L. and Wang, T. 2025. Impact of particle size distribution and morphology of starch on microstructural–functional changes of dough. *Lwt-Food Science and Technology,* **215**: 117251.

Hundekari, S.H. 2018. Development of starch based edible film from cassava and jackfruit seed starch (M. Tech. dissertation, College of Agricultural engineering and technology, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeeth Dapoli.)

Juhasz, R. and Salgo, A. 2008. Pasting behavior of amylose, amylopectin and their mixtures as determined by RVA curves and first derivatives. *Starch-Stärke*, **60**(2):70-78.

Karadbhajne, S.V. and Yatin Sawant, Y.S. 2014. Comparison of physico-chemical properties of modified jackfruit starch with maize starch. *International Journal of ChemTech Research,* **6**(1): 487-494.

Kaur, S., Bedi, M., Singh, S., Kour, N., Bhatti, S.S., Bhatia, A., Kumar, M. and Kumar, R. 2024. Monoculture of crops: A challenge in attaining food security. In *Advances in Food Security and Sustainability*, **9**: 197-213.

Kavlani, N., Sharma, V. and Singh, L. 2012. Various techniques for the modification of starch and the applications of its derivatives. *International Research Journal of Pharmacy*, **3**(5): 25-31.

Khang, V.C., Thanh, V.T., Nhan, N.P.T., Yen Nhi, T.T., Nguyen, D.T., Luu, T.T. and Quoc, N.T. 2020. Physico-chemical evaluation of jackfruit seed starch and its application in cupcake. In *IOP Conference Series: Materials Science and Engineering*, **991**(1): 012031. IOP Publishing.

Khuswah, L., Sharma, A.K. and Sharma, S. 2025. Harnessing the potential of jackfruit seeds as a bio-coagulant to treat sewage: a review. *International Research Journal of Modernization in Engineering Technology and Science*, **7**(12): 1545-1550.

Kittipongpatana, O.S. and Kittipongpatana, N. 2011. Preparation and physico-chemical properties of modified jackfruit starches. *LWT-Food Science and Technology*, **44**(8): 1766-1773.

Kittipongpatana, O.S. and Kittipongpatana, N. 2015. Resistant starch contents of native and heat-moisture treated jackfruit seed starch. *The Scientific World Journal*, (1): 519854.

Kuakpetoon, D. and Wang, Y.J. 2006. Structural characteristics and physico-chemical properties of oxidized corn starches varying in amylose content. *Carbohydrate Research*, **341**(11): 1896-1915.

Kumar, P., Chaudhary, V., Patil, R., Deshmukh, R.K., Gaikwad, K.K. and Kishore, A. 2026. Valorization of jackfruit seed and pomelo peel for coating on wrapping paper for active food packaging. *Journal of Coatings Technology and Research*, **23**(2): 703-715.

Kumar, R. and Khatkar, B.S. 2017. Thermal, pasting and morphological properties of starch granules of wheat (*Triticum aestivum* L.) varieties. *Journal of food science and technology*, **54**(8): 2403-2410.

Kushwaha, R., Kaur, S. and Kaur, D. 2023a. Potential of jackfruit (*Artocarpus heterophyllus* Lam.) seed starch as an alternative to the commercial starch source–A review. *Food Reviews International*, **39**(5): 2635-2654.

Kushwaha, R., Singh, M., Singh, V., Kaur, S. and Kaur, D. 2025. Synthesis and Characterization of Biofilms using Native and Acid Modified Jackfruit Seed Starch. *Nutrition and Food science International Journal*, **14**(1): 555877.

Kushwaha, R., Singh, V., Kaur, S. and Kaur, D. 2023b. Characterization and comparative analysis of starches from seeds of five jackfruit cultivars. *Starch-Stärke*, **75**(5-6): p.2200208.

Li, H., Prakash, S., Nicholson, T.M., Fitzgerald, M.A. and Gilbert, R.G. 2016. The importance of amylose and amylopectin fine structure for textural properties of cooked rice grains. *Food Chemistry*, **196**: 702-711.

Luciano, C.G., Landi Franco, C.M., Ayala Valencia, G., do Amaral Sobral, P.J. and Freitas Moraes, I.C. 2017. Evaluation of extraction method on the structure and physico-chemical properties of starch from seeds of two jackfruit varieties. *Starch-Stärke*, **69**(11-12): 1700078.

Ma, M., Wen, Y., Zhang, C., Xu, Z., Li, H., Sui, Z. and Corke, H. 2022. Extraction and characterization of starch granule-associated surface and channel lipids from small-granule starches that affect physico-chemical properties. *Food Hydrocolloids*, **126**: 107370.

Madruga, M.S., de Albuquerque, F.S.M., Silva, I.R.A., do Amaral, D.S., Magnani, M. and Neto, V.Q. 2014. Chemical, morphological and functional properties of Brazilian jackfruit (*Artocarpus heterophyllus* L.) seeds starch. *Food Chemistry*, **143**: 440-445.

Manianga, A., Ekuban, C.A., Lukambagire, I., Bose, C. and Sabarinath, S. 2024. Examining underutilized jackfruit (*Artocarpus heterophyllus*) seeds as a potential source of human subsistence in the Byse community, India. *Frontiers in Sustainable Food Systems*, **8**: 1377076.

Naknaen, P. 2014. Physico-chemical, thermal, pasting and microstructure properties of hydroxypropylated jackfruit seed starch prepared by etherification with propylene oxide. *Food Biophysics*, **9**(3): 249-259.

Naknaen, P., Tobkaew, W. and Chaichaleom, S. 2017. Properties of jackfruit seed starch oxidized with different levels of sodium hypochlorite. *International Journal of Food Properties*, **20**(5): 979-996.

Nayak, A.K., Alkahtani, S. and Hasnain, M.S. 2021. Jackfruit seed starch-based composite beads for controlled drug release. In Nayak, A.K., Alkahtani, S. and Hasnain, M.S. (Eds.), *Polymeric and natural composites: Materials, manufacturing and biomedical applications*, 213-240. Springer.

Neelanjana, J., Sharma, S. and Derline Jose 2023. Health benefits of jackfruit (*Artocarpus heterophyllus* Lam.) seeds: A review. *The Pharma Innovation Journal*, **12**(6): 879-888.

Nguyen, T.T.T., Truong, N.L.Q., Chiem, T.N.Q., Truong, L.D.P., Nguyen, T.T.T. and Van Tran, T. 2025. Development of intelligent films based on jackfruit seed starch/ polyvinyl alcohol incorporated with purple sweet potato peel anthocynanin as an indicator. *International Journal of Biological Macromolecules*, **319**: 145436.

Noor, F., Rahman, M.J., Mahomud, M.S., Akter, M.S., Talukder, M.A.I. and Ahmed, M. 2014. Physico-chemical properties of flour and extraction of starch from jackfruit seed. *International Journal of Nutrition and Food Sciences*, **3**(4): 347-354.

Ouyang, Q., Wang, X., Xiao, Y., Luo, F., Lin, Q. and Ding, Y. 2021. Structural changes of A-, B-and C-type starches of corn, potato and pea as influenced by sonication temperature and their relationships with digestibility. *Food Chemistry*, **358**: 129858.

Oyeyinka, S.A., Akintayo, O.A., Adebo, O.A., Kayitesi, E. and Njobeh, P.B. 2021. A review on the physico-chemical properties of starches modified by microwave alone and in combination with other methods. *International Journal of Biological Macromolecules*, **176**: 87-95.

Patel, A.S., Kar, A. and Mohapatra, D. 2020. Development of microencapsulated anthocyanin-rich powder using soy protein isolate, jackfruit seed starch and an emulsifier (NBRE-15) as encapsulating materials. *Scientific Reports*, **10**(1): 10198.

Perez, E., Bahnassey, Y.A. and Breene, W.M. 1993. A simple laboratory scale method for isolation of Amaranth starch. *Starch/Starke*, **6**(1): 211–214.

Phrukwiwattanakul, P., Wichienchotand, S. and Sirivongpaisal, P. 2014. Comparative studies on physico-chemical properties of starches from jackfruit seed and mung bean. *International Journal of Food Properties*, **17**(9): 1965-1976.

Phukan, H., Singha, L.I. and Mitra, P.K. 2018. Hepato-protective effect of aqueous extract of seed, leaf and fruit of jackfruit (*Artocarpus heterophyllus* lam.) Against ccl4 induced hepatotoxicity on swiss albino mice. *World J. Pharm. Res.*, **7**(9): 766-79.

Punia, S. 2020. Barley starch modifications: Physical, chemical and enzymatic - a review. *International Journal of Biological Macromolecules,* **144**: 578–585.

Ranasinghe, R.A.S.N., Maduwanthi, S.D.T. and Marapana, R.A.U.J. 2019. Nutritional and Health Benefits of Jackfruit (*Artocarpus heterophyllus* Lam.): A Review. *International Journal of Food Science,* (1): 4327183.

Rengsutthi, K. and Charoenrein, S. 2011. Physico-chemical properties of jackfruit seed starch (*Artocarpus heterophyllus*) and its application as a thickener and stabilizer in chilli sauce. *LWT- Food Science and Technology*, **44**(5): 1309–1313.

Roy, T. and Zhou, Y. 2026. From agricultural waste to building insulation: a chemical-free composite from banana stem and jackfruit seed starch. *Bioresource Technology*, **452**: 134591.

Saha, S., Sarker, M., Haque, A.R., Nayeem, T.A. and Maukeeb, A.R. 2022. A review on tropical fruit: jackfruit (*Artocarpus heterophyllus*). *Asian Journal of Advances in Research*, **5**(1): 298-307.

Sandhu, K.S., Singh, N. and Kaur, M. 2004. Characteristics of the different corn types and their grain fractions: physico-chemical, thermal, morphological, and rheological properties of starches. *Journal of Food Engineering*, **64**(1): 119-127.

Santhosh, R. and Sarkar, P. 2022. Jackfruit seed starch/ tamarind kernel xyloglucan/zinc oxide nanoparticles-based composite films: Preparation, characterization, and application on tomato (*Solanum lycopersicum*) fruits. *Food Hydrocolloids*, **133**: 107917.

Sargar, Y.A. and Swami, S.B. 2025. Evaluation of the Rheological Characteristics of Various Blends of Soup Mixes by Using Jackfruit Seed Starch as Thickener. *Int. J. Food Ferment. Technol.,* **15**(02): 433-442.

Singan, Grace and Liew, Kang Chiang. 2016. Hydrolyzation of Edible Starches: Their Preparations and Properties. *Materials Science Forum,* **875**: 63-76.

Singh, J. and Singh, N. 2001. Studies on the morphological, thermal and rheological properties of starch separated from some Indian potato cultivars. *Food Chemistry,* **75**(1): 67–77.

Singh, J., Kaur, L. and McCarthy, O.J. 2007. Factors influencing the physico-chemical, morphological, thermal and rheological properties of some chemically modified starches for food applications—A review. *Food Hydrocolloids*, **21**(1): 1-22.

Sukhija, S., Singh, S. and Riar, C.S. 2016. Effect of oxidation, cross-linking and dual modification on physico-chemical, crystallinity, morphological, pasting and thermal characteristics of elephant foot yam (*Amorphophallus paeoniifolius*) starch. *Food Hydrocolloids*, **55**: 56-64.

Swami, Shrikant and Kalse, Sandeep. 2019. Jackfruit (*Artocarpus heterophyllus*): Biodiversity, Nutritional Contents, and Health. *In:* Mérillon, JM., Ramawat, K.G. (eds) *Bioactive molecules in food*, 2237-2259. Springer, Cham.

Tharanathan, R.N. 2005. Starch—value addition by modification. *Critical Reviews in Food Science and Nutrition*, **45**(5): 371-384.

Tran, P.L., Dang, H.D.N., Do, V.H., Kim, Y.L., Park, S., Yoo, S.H., Lee, S.Y. and Kim, Y.R. 2015. Physico-chemical properties of native and partially gelatinized high-amylose jackfruit (*Artocarpus heterophyllus* Lam) seed starch. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology*, **62**(2): 1091–1098.

Tulyathan, V., Tananuwong, K., Songjinda, P. and Jaiboon, N. 2002. Some physico-chemical properties of jackfruit (*Artocarpus heterophyllus* Lam) seed flour and starch. *Science Asia*, **28**(1): 37-41.

Wang, B., Zhong, Z., Wang, Y., Yuan, S., Jiang, Y., Li, Z., Li, Y., Yan, Z., Meng, L. and Qiu, L. 2023. Recent progress of starch modification assisted by ultrasonic wave. *Food Science and Technology*, **43**: 107522.

Wang, L. and Tong, L. 2024. Production and Properties of Starch: Current Research. *Molecules (Basel, Switzerland)*, **29**(3): 646.

Wang, Y., Ou, X., Al-Maqtari, Q.A., He, H.J. and Othman, N. 2024. Evaluation of amylose content: Structural and functional properties, analytical techniques, and future prospects. *Food Chemistry, X*, **24**: 101830.

Wong, K.T., Poh, G.Y.Y., Goh, K.K.T., Wee, M.S.M. and Jeyakumar Henry, C. 2021. Comparison of physico-chemical properties of jackfruit seed starch with potato and rice starches. *International Journal of Food Properties*, **24**(1): 364-379.

Yazid, N.S.M., Abdullah, N. and Muhammad, N. 2019. Comparison of chemical, functional and morphological characteristics of jackfruit (*Artocarpus heterophyllus* Lam.) (J33) seed starch and commercial native starches. In *IOP Conference Series: Earth and Environmental Science*, **269**(1): 012031. IOP Publishing.

Yazid, N.S.M., Abdullah, N., Muhammad, N. and Matias-Peralta, H.M. 2018. Application of starch and starch-based products in food industry. *Journal of Science and Technology*, **10**(2): 144-174.

Ye, J., Hu, X., Luo, S., Liu, W., Chen, J., Zeng, Z. and Liu, C. 2018. Properties of starch after extrusion: A review. *Starch-Stärke*, **70**(11-12): 1700110.

Yu, S., Ma, Y. and Sun, D.W. 2009. Impact of amylose content on starch retrogradation and texture of cooked milled rice during storage. *Journal of Cereal Science*, **50**(2): 139-144.

Zhang, J., Li, J. and Fan, L. 2024a. Effect of starch granule size on the properties of dough and the oil absorption of fried potato crisps. *International Journal of Biological Macromolecules*, **268**: 131844.

Zhang, J., Tao, L., Yang, S., Li, Y., Wu, Q., Song, S. and Yu, L. 2024b. Water absorption behavior of starch: A review of its determination methods, influencing factors, directional modification, and food applications. *Trends in Food Science & Technology*, **144**: 104321.

Zhang, L., Pang, L. and Zhang, Z. 2011. Preparation of maltose syrup from starch of jackfruit seeds by β-amylase. *Journal of Guangdong University of Petrochemical Technology*, **21**(6): 7–11.

Zhang, Y., Hu, M., Zhu, K., Wu, G. and Tan, L. 2018. Functional properties and utilization of *Artocarpus heterophyllus* Lam seed starch from new species in China. *International Journal of Biological Macromolecules*, **107**: 1395-1405.

Zhang, Y., Li, B., Xu, F., He, S., Zhang, Y., Sun, L., Zhu, K., Li, S., Wu, G. and Tan, L. 2021. Jackfruit starch: Composition, structure, functional properties, modifications and applications. *Trends in Food Science & Technology*, **107**: 268-283.

Zhang, Y., Liu, J., Chen, X., Xu, F., Zhang, X., Zhu, K., Zhang, J. and Zhang, Y. 2025. Type 3 resistant starch prepared from jackfruit alleviated the hyperlipidemia via gut microbiota regulation. *International Journal of Biological Macromolecules*, **310**: 143452.

Zhang, Y., Zuo, H., Xu, F., Zhu, K., Tan, L., Dong, W. and Wu, G. 2021. The digestion mechanism of jackfruit seed starch using improved extrusion cooking technology. *Food Hydrocolloids*, **110**: 106154.

Zhao, J., Chen, Z., Jin, Z., Buwalda, P., Gruppen, H. and Schols, H.A. 2015. Effects of granule size of cross-linked and hydroxypropylated sweet potato starches on their physico-chemical properties. *Journal of Agricultural and Food Chemistry*, **63**(18): 4646-4654.