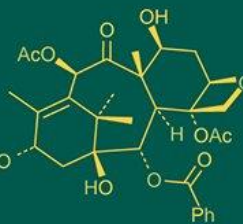
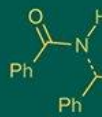


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Physicochemical and functional characterization of jackfruit seed starch extracted by aqueous and alkaline methods

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Abstract

Jackfruit (*Artocarpus heterophyllus*) seeds are ample agro-industrial by-products whose starch potential remains largely underutilized. This study focuses on extraction of starch from jackfruit seed flour through two methods aqueous (distilled water) and alkaline (0.5% NaOH) and compared their physicochemical and functional profiles to determine the more suitable precedent for biodegradable packaging film development. The alkaline method yielded significantly greater starch recovery (47.8 ± 1.3 g/100 g) than the aqueous method (38.75 ± 1.1 g/100 g), due to protein and non-starch polysaccharide solubilization by NaOH. However, the aqueous-extracted starch exhibited consistently more effective functional characteristics, including higher Water Absorption Index (3.18 ± 0.09 g/g), Fat Absorption Capacity ($180.4 \pm 3.5\%$), Swelling Capacity (9.87 ± 0.26 g/g), Dispersibility ($82.0 \pm 1.7\%$), and Water Solubility Index ($10.90 \pm 0.42\%$), all of which are desirable for forming cohesive, homogeneous starch-based films. Alkali treatment modified granule structure and reduced these functional attributes despite its quantitative advantage. Based on the complete functional profile, aqueous-extracted jackfruit seed starch was selected as the preferred substrate for biodegradable packaging film development. These findings underscore the trade-off between extraction yield and functional quality, and support the use of jackfruit seed starch as a renewable, sustainable biopolymer source for active food packaging applications.

Keywords: Jackfruit seed starch, alkaline extraction, aqueous extraction, functional properties, biodegradable packaging, biopolymer

1. Introduction

The global production and disposal of synthetic plastics has reached critical proportions, with over 400 million metric tons generated annually, the vast majority of which ends up in landfills or natural ecosystems (Domínguez-Robles *et al.*, 2025) [3]. Conventional petroleum-derived packaging polymers resist microbial, chemical, and physical degradation, generating persistent environmental contaminants. Regulatory interventions, such as the Chinese plastic bag restriction studied by He (2012) [6], have demonstrated that policy alone reduces consumption by approximately 49%, but structural alternatives in the form of truly biodegradable materials are needed to close the gap. Against this backdrop, research into biopolymer-based packaging films derived from renewable, food-safe raw materials has intensified considerably over the past two decades (Imran *et al.*, 2010) [8].

Among biopolymers, starch stands out as one of the most accessible, affordable, and chemically versatile film-forming agents. Starches from potato, wheat, rice, maize, and cassava have all been investigated for their packaging potential (Flores *et al.*, 2007; Santana *et al.*, 2018) [4, 14]. Yet a largely untapped source lies in the seeds of jackfruit (*Artocarpus heterophyllus*), a tropical tree whose global annual production exceeds three million tons. The fleshy fruit is consumed widely across South and Southeast Asia, while the seeds comprising 10-15% of the fruit by weight are typically discarded as waste. Jackfruit seeds contain 60-80% starch on a dry basis, making them an economically and ecologically attractive precursor for biopolymer applications (Nurul Aini *et al.*, 2022; Naknaen *et al.*, 2017) [12, 10].

The quality and functional characteristics of any starch preparation are profoundly shaped by the method used to isolate it from the source material.

Two widely employed approaches aqueous (distilled water) extraction and alkaline (NaOH) extraction differ fundamentally in the chemical environment they create during starch liberation. Aqueous extraction is gentle, preserving native granule architecture and associated hydrophilic components, while alkaline extraction disrupts cell-wall proteins and non-starch polysaccharides more aggressively, often increasing yield at the cost of altering the starch's surface chemistry and structural order (Naknaen *et al.*, 2017; Lee *et al.*, 2007) ^[10, 9]. Understanding how these differences translate into measurable functional properties specifically water absorption, water solubility, swelling behavior, fat absorption, and dispersibility is therefore essential for selecting an appropriate extraction protocol when the intended downstream application is film casting.

Polyvinyl alcohol (PVA) is frequently co-incorporated with starch in biodegradable film matrices because of its exceptional mechanical strength, flexibility, and compatibility with polysaccharide networks through hydrogen bonding (Abdullah *et al.*, 2017; Oyeoka *et al.*, 2021) ^[1, 13]. Glycerol serves as the plasticizer of choice, relaxing inter-chain hydrogen bonds within the starch-PVA network and imparting the elongation and pliability essential for real-world packaging performance (Santana *et al.*, 2018) ^[14]. Building on this composite framework, the present study focused exclusively on the first and foundational objective: systematically comparing distilled water and alkaline extraction of jackfruit seed starch with respect to yield and key functional parameters, and using those data to rationally select the extraction method best suited to subsequent biodegradable packaging film development.

The functional properties examined WAI, WSI, swelling capacity, fat absorption capacity, and dispersibility are direct determinants of film-forming behavior. WAI reflects the starch matrix's capacity to retain absorbed water and signals granule swelling potential upon gelatinization, which drives the formation of a continuous film network. WSI indicates the proportion of soluble material available to participate in intermolecular structuring of the gel phase. Dispersibility measures how uniformly a starch suspension distributes in water, a prerequisite for void-free, homogeneous cast films. These parameters collectively determine whether a starch lot will produce films of acceptable optical clarity, mechanical integrity, and barrier performance key criteria for active food packaging (Nguyen *et al.*, 2022; Flores *et al.*, 2007) ^[11, 4].

2. Materials and Methods

2.1 Raw Materials

Jackfruit seeds were collected from locally procured mature jackfruit (*Artocarpus heterophyllus*) from Bapatla district, Andhra Pradesh, India. Seeds were washed, peeled, sliced, shade-dried, and ground into fine flour using a laboratory mill. The flour was passed through a 60-mesh sieve and stored at room temperature in sealed polyethylene bags until use. All reagents including sodium hydroxide (NaOH, analytical grade) were procured from standard suppliers.

2.2 Extraction of Jackfruit Seed Starch

2.2.1 Aqueous (Distilled Water) Extraction

The aqueous extraction procedure was adapted from Singh and Singh (2001) ^[15] with minor modifications. Jackfruit seed flour (5 g) was dispersed in 100 mL of distilled water and allowed to soak with continuous magnetic stirring at

room temperature for 6 hours. The resulting slurry was passed through a 212-mesh stainless-steel sieve, and the retained residue was washed three additional times with distilled water to ensure complete starch recovery. The combined filtrates were transferred to clean beakers and allowed to settle overnight at 4 °C to facilitate starch precipitation. The clear supernatant was carefully decanted, and the crude starch sediment was resuspended in distilled water, stirred, and allowed to sediment again; this washing cycle was repeated three times. The washed starch cake was then dried in a tray dryer at 50 °C for 24 hours, ground with a mortar and pestle, and stored at room temperature in an airtight container. The 6-hour soaking period was selected on the basis of maximum starch yield observed during preliminary trials.

2.2.2 Alkaline (NaOH) Extraction

Alkaline extraction was carried out following a protocol modified from Singh and Singh (2001) ^[15]. Jackfruit seed flour (5 g) was dispersed in 100 mL of 0.5% NaOH solution and soaked with continuous stirring at room temperature for 6 hours. The concentration of 0.5% NaOH was selected after preliminary optimization trials at 0.1%, 0.25%, and 0.5% (w/v), which demonstrated the highest starch yield at 0.5%. The slurry was filtered through a 212-mesh stainless sieve, and the residue was washed three times with distilled water. The combined filtrate was adjusted to neutral pH using dilute HCl and then kept overnight at 4 °C for starch sedimentation. The supernatant was discarded, and the crude starch was purified by repeated washing with distilled water as described above. Drying, grinding, and storage conditions were identical to those used for the aqueous extraction method.

2.3 Starch Yield

Yield was determined gravimetrically and expressed as grams of dried starch obtained per 100 g of jackfruit seed flour, using the formula:

$$\text{Yield (g/100 g)} = [(\text{Initial weight} - \text{Final weight}) / \text{Initial weight}] \times 100$$

2.4 Determination of Water Absorption Index (WAI) and Water Solubility Index (WSI)

WAI and WSI were determined using the method of Anderson (2001). Starch (0.83 g dry basis) was suspended in 10 mL of distilled water and stirred for 30 minutes. The suspension was centrifuged at 4000 rpm for 30 minutes. The supernatant was decanted into a pre-weighed Petri dish and oven-dried at 70 °C overnight to determine the weight of dissolved solids. WAI and WSI were computed as follows:

$$\text{WAI (g/g)} = \text{Weight of sediment} / \text{Weight of dry sample}$$

$$\text{WSI (\%)} = (\text{Weight of dissolved solids in supernatant} / \text{Weight of dry sample}) \times 100$$

2.5 Swelling Capacity

Swelling capacity was calculated according to Lai and Cheng (2004) using the equation:

$$\text{SWC (g/g)} = \text{Weight of sediment} / [\text{Dry weight of sample} \times (1 - \text{WSI}/100)]$$

2.6 Fat Absorption Capacity (FAC)

Fat absorption capacity was determined by blending 1 g of starch with 10 mL of refined sunflower oil. After mixing for 30 seconds, the mixture was allowed to rest for 30 minutes followed by centrifugation at 3000 rpm for 25 minutes. The volume of free oil not absorbed by the starch was measured and FAC was expressed as the percentage of oil retained relative to the initial sample weight.

2.7 Dispersibility

Dispersibility was measured by dispersing 1 g of starch in 100 mL of distilled water using a magnetic stirrer and evaluating the homogeneity of the suspension after 30 minutes. The proportion of starch uniformly distributed relative to the total starch added was expressed as dispersibility (%).

2.8 Statistical Analysis

All experiments were carried out in triplicate, and results are expressed as mean $\pm$ standard deviation (SD). Statistical differences between the two extraction methods were evaluated using one-way analysis of variance (ANOVA) in Minitab software. Means were separated by Tukey's Honest Significant Difference (HSD) test at a significance level of $p < 0.05$. Means sharing the same superscript letter within a row are not significantly different.

3. Results and Discussion

The physicochemical and functional properties of jackfruit seed starch extracted by the distilled water and alkaline (0.5% NaOH) methods are summarized in Table 1. Significant differences ($p < 0.05$) were observed between the two methods for all parameters evaluated, revealing a complex interplay between extraction chemistry, granule architecture, and functional performance.

3.1 Starch Yield

The alkaline method produced a substantially higher starch yield (47.8 ± 1.3 g/100 g) compared to distilled water extraction (38.75 ± 1.1 g/100 g), a difference that was statistically significant ($p < 0.05$). This quantitative advantage arises because NaOH at 0.5% concentration partially solubilizes cell-wall proteins and non-starch polysaccharides that otherwise remain bound to starch granules, effectively liberating a greater proportion of the starch granule pool from the seed matrix (Naknaen *et al.*, 2017) [10]. The alkaline conditions disrupt the protein network surrounding starch granules, reducing the mechanical entrapment of granules within the cotyledon matrix and permitting more complete sedimentation during precipitation. Similar yield advantages of alkaline extraction have been documented for lentil starch by Lee *et al.* (2007) [9], who reported that NaOH treatment optimized extraction efficiency without irreversibly damaging granule crystallinity at concentrations $\leq 0.5\%$. Despite its lower absolute yield, the aqueous method preserves the native composition of the starch granule surface, including a proportion of bound lipids and proteins that contribute to the functional characteristics discussed below.

3.2 Water Solubility Index (WSI)

Contrary to the yield trend, WSI was significantly higher in aqueous-extracted starch ($10.90 \pm 0.42\%$) than in alkali-extracted starch ($7.85 \pm 0.31\%$). The elevated WSI of the

aqueous preparation reflects the retention of naturally occurring soluble starch fractions and short-chain amylose molecules that are washed away during the more aggressive alkaline process. Under alkaline conditions, the partial chemical gelatinization of granule surfaces — described by He and Kong (2025) [7] — restructures the granule matrix in a way that reduces the proportion of components that readily solubilize in water, even as the total granule mass recovered is greater. A higher WSI is functionally advantageous in film formation, as it indicates a greater concentration of dissolved macromolecules in the casting solution, which participate in intermolecular entanglement and hydrogen bonding to produce a more cohesive gel phase upon gelatinization (Flores *et al.*, 2007) [4].

3.3 Water Absorption Index (WAI)

Aqueous-extracted starch showed a higher WAI (3.18 ± 0.09 g/g) relative to alkali-extracted starch (2.74 ± 0.08 g/g). WAI is a measure of the starch granule's capacity to absorb and retain water — essentially reflecting the integrity and swelling potential of the granule. The comparatively higher WAI of aqueous-extracted starch points to the preservation of hydrophilic surface components, including residual proteins and lipid-amylose complexes, which form an absorbent outer layer on the granule. Naknaen *et al.* (2017) [10] likewise reported that alkali-processed starches exhibit diminished WAI due to the removal of proteins that otherwise enhance water retention. From a film-processing perspective, a higher WAI is desirable because it signals that the starch granules will swell uniformly during gelatinization, creating a continuous and cohesive matrix rather than a particulate or heterogeneous film structure (Nguyen *et al.*, 2022) [11].

3.4 Fat Absorption Capacity (FAC)

The fat absorption capacity of aqueous-extracted starch ($180.4 \pm 3.5\%$) significantly exceeded that of alkali-extracted starch ($151.6 \pm 2.8\%$). FAC reflects the ability of starch to entrap lipid molecules within granule pores or via surface interactions. Native starch granules carry a coat of lipid-protein complexes on their surface; during alkaline processing, NaOH removes or denatures these components, specifically the lipids, reducing affinity for non-polar molecules (Ghoshal and Kaur, 2023) [5]. Starch-lipid interactions play a functional role in film matrices co-formulated with hydrophobic additives such as essential oils: starch preparations with higher FAC are better equipped to distribute and entrap oil droplets uniformly, reducing phase separation and maintaining film homogeneity (Vianna *et al.*, 2021) [16]. This consideration is particularly relevant in the context of the present study, where subsequent film formulations incorporated Piper betel leaf essential oil as an active ingredient.

3.5 Swelling Capacity

Aqueous-extracted starch recorded a swelling capacity of 9.87 ± 0.26 g/g, while the alkali-extracted counterpart swelled to only 8.42 ± 0.24 g/g — a statistically significant difference ($p < 0.05$). Swelling capacity quantifies the degree of granule hydration and expansion upon heating in water, a process central to starch gelatinization and film casting. The reduced swelling of alkali-extracted starch aligns with reports by Lee *et al.* (2007) [9], who demonstrated that alkaline processing removes surface lipids and modifies

crystalline regions, yielding a more rigid granule interior that resists water penetration. Additionally, the partial chemical gelatinization occurring at the granule surface under alkaline conditions may pre-disrupt the natural swelling mechanism, leading to a less expansive hydration behavior during subsequent aqueous heating. Higher swelling capacity in the aqueous extract translates to a greater volume of gelatinized starch paste per unit mass, which produces thicker, better-cross-linked film structures upon drying.

3.6 Dispersibility

Dispersibility was notably higher for aqueous-extracted starch ($82.0 \pm 1.7\%$) than for alkali-extracted starch ($74.5 \pm 1.5\%$). This parameter reflects the ease and uniformity with which starch particles distribute in an aqueous medium. The lower dispersibility of alkali-extracted starch may be linked to the surface modifications induced by NaOH treatment, which can cause partial aggregation or compaction of granule surfaces, reducing their tendency to spread uniformly in water. For the practical purpose of film casting, high dispersibility is an important prerequisite, as it directly determines the optical homogeneity and structural uniformity of the final film. Uneven dispersibility leads to localized areas of high

granule density within the casting solution, which produce heterogeneous films with mechanical weak points (Flores *et al.*, 2007)^[4].

3.7 Basis for Method Selection

Taken together, the data reveal a fundamental trade-off between the two extraction strategies: alkaline extraction maximizes starch yield, while aqueous extraction preserves the functional attributes that are most directly relevant to film performance. Although the 9 g/100 g yield advantage of alkali extraction is economically meaningful at scale, functional properties — particularly WAI, dispersibility, swelling capacity, and FAC — are the primary determinants of whether a starch preparation will form continuous, mechanically coherent, optically uniform films upon casting. The aqueous-extracted jackfruit seed starch exhibited superior scores on every functional parameter measured, leading to its selection as the substrate for all subsequent biodegradable packaging film formulations in this study. This choice aligns with the recommendation of Nguyen *et al.* (2022)^[11], who confirmed that granule integrity and swelling potential are the rate-limiting factors in producing films of acceptable barrier and mechanical properties from jackfruit seed starch.

Table 1: Physicochemical and functional properties of jackfruit seed starch extracted by aqueous and alkaline methods (Mean $\pm$ SD, n = 3). Different superscript letters within a row indicate significant differences ($p < 0.05$, Tukey's HSD test).

Property	Aqueous Extraction (Distilled Water)	Alkaline Extraction (0.5% NaOH)
Yield of Starch (g/100 g)	38.75 ± 1.1^b	47.80 ± 1.3^a
Water Solubility Index-WSI (%)	10.90 ± 0.42^a	7.85 ± 0.31^b
Water Absorption Index-WAI (g/g)	3.18 ± 0.09^a	2.74 ± 0.08^b
Fat Absorption Capacity (%)	180.4 ± 3.5^a	151.6 ± 2.8^b
Swelling Capacity (g/g)	9.87 ± 0.26^a	8.42 ± 0.24^b
Dispersibility (%)	82.0 ± 1.7^a	74.5 ± 1.5^b

4. Conclusion

This investigation systematically compared the aqueous and alkaline extraction of starch from jackfruit seeds across six functional parameters critical to film-forming application. While alkaline extraction offered a numerically superior yield (47.8 vs. 38.75 g/100 g), aqueous extraction consistently yielded starch with higher water absorption index, water solubility index, fat absorption capacity, swelling capacity, and dispersibility the collective functional fingerprint of a starch well suited to homogeneous film casting. The structural modifications imposed by NaOH, though productive in freeing more starch from the seed matrix, compromise precisely those surface and granule-level properties that govern gelatinization dynamics, film continuity, and compatibility with hydrophobic active ingredients. Aqueous-extracted jackfruit seed starch is therefore recommended as the preferred substrate when functionality, rather than raw yield, is the primary optimization criterion. These results establish a clear, data-driven justification for the downstream film development phase and contribute to a growing body of evidence supporting jackfruit seed starch as a viable, sustainable biopolymer feedstock for active food packaging.

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