



Novel Frontier of arrowroot starch: Extraction, modification, characterization and application in food industry

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Abstract

Arrowroot (*Maranta arundinacea* L.) starch, a versatile carbohydrate source with high amylose content and unique functional properties, holds significant potential in food and non-food industries. This study highlights advancements in the extraction, characterization, modification, and applications of arrowroot starch (AS). Traditional extraction methods often yield suboptimal starch quality because of high granular damage. Innovative clean technologies, such as ultrasound- and microwave-assisted extraction, have demonstrated improved yields and purity while minimizing environmental impacts. Modification techniques, including thermal, non-thermal, chemical, and enzymatic processes, were explored to address the limitations of native AS, such as retrogradation and low thermal stability. These modifications enhance its functional properties, such as water absorption, swelling, solubility, and rheological adaptability, enabling its application in food formulations, pharmaceutical excipients, and biodegradable films. Comprehensive analyses, including Fourier transform infrared spectroscopy, SEM, and XRD, revealed the structural and molecular transformations induced by these modifications, which enhance the crystallinity and physicochemical stability of AS. Additionally, applications in gluten-free baking, edible films, and as a 3D printing bio-ink were investigated, demonstrating its versatility in innovative and sustainable product development. This study underscores the need for increased awareness, optimized cultivation practices, and a focus on green technologies to expand the industrial application of AS.

KEYWORDS

digestibility, food application, functional properties, green modification, nutritional value

1 | INTRODUCTION

Starch serves as the primary carbohydrate source in plants and is a crucial part of the human diet. It is widely utilized in the food industry for numerous applications because of its valuable properties. In plants, starch is primarily stored in the amyloplasts of storage sites

such as tubers and seeds, as well as in the chloroplasts of leaves in higher plants. Globally, only selected crops are predominantly cultivated for production of starch. The most significant sources include maize, cassava, potato, and wheat, whereas other crops such as mung beans, rice, sweet potato, sago, and arrowroot, contribute smaller quantities to the overall starch supply.^{1,2} Starch is composed of two

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distinct types of macromolecules: amylose and amylopectin. Amylose is primarily a linear polymer, consisting of anhydro glucose units connected by α (1,4) glycosidic bonds. This molecule typically has a molecular weight ranging from 5×10^5 – 10^6 . In contrast, amylopectin is characterized by its highly branched structure, which includes both α (1,4) linkages and approximately 2%–5% of α (1,6) linked branches. The molecular weight of amylopectin can reach several million, making it significantly larger than amylose.³

The main sources of starch are tubers, which contain about 65%–85% starch,⁴ and cereals, which range from 40% to 90% starch. Roots typically have 30%–70% starch, whereas nuts provide around 25%–50%. Some immature fruits, such as bananas and mangoes, also contain significant amounts of starch, making up about 70% of their dry weight.⁵ Commercial starches, derived from sources such as corn, potato, and tapioca, serve as vital food additives for stabilizing, thickening, and texturizing products while enhancing moisture retention and gelatinization. Beyond food, they find applications in textiles, construction, pharmaceuticals, and paper industries, showcasing their versatility and importance across multiple sectors.⁶ Therefore, in this study arrowroot crop was employed. Arrowroot (*Maranta arundinacea* L.) is a starch-rich (16%–25%) tuber plant characterized by its elongated arrow-like rhizome.¹ Nutritionally, arrowhead tubers are composed of approximately 54.60% starch, 16.4% protein, 4.76% ash, and 0.47% fat. Additionally, the amylose content in arrowhead tubers is around 30.73%.⁷ Though, the desirable digestible and herbal properties,⁸ thickening, wheat alternative (because of its gluten free property), bread ingredient, and film-forming ability (biopolymers, fibers, and edible films) of the extracted starch opens up the possibility for it to be used in a wide range of applications, much like other commercially available tuber starches (cassava and potato). Despite its potential, arrowroot tubers have been largely undervalued and underutilized.^{1,9}

Native starches have presented several challenges, mainly because of their low resistance to heat and shear, high tendency to retrograde, and increased paste opacity.¹⁰ To address these challenges, researchers had explored different modification techniques via chemical, physical, and enzymatic methods. Increasing consumer awareness about the potential health risks associated with chemical additives has led to a decline in the use of chemically modified products. In contrast, physical modification methods, such as thermal and non-thermal treatments, can effectively alter starch properties without introducing harmful chemical agents. Today, researchers are favoring “clean” and “green” methods for starch modification because they are eco-friendly, leaving no chemical residues in the product or environment.¹¹ Traditionally, the method of starch extraction from arrowroot encompasses cleaning, dicing and peeling of rhizomes, following milling by adding water to extract starch.¹ Nevertheless, the traditional method is found inadequate for extracting starch from arrowroot because of lower yield. To overcome this, scholars are emphasizing on novel techniques using clean and green technology such as enzyme assisted extraction, cold plasma technology, ultrasound-assisted extraction, microwave assisted extraction, and more which improves both efficiency and purity.^{12–14} Previously,

researchers had modified arrowroot starch (AS) using different methods, such as by chemical treatments: Octenyl succinic anhydride, acetylation, acidic hydrolysis,¹⁵ hydroxypropylation,¹⁶ substitution and crosslinking¹⁷; physical technologies were identified as autoclave-cooling,^{18,19} hydrothermal treatments²⁰, and enzymatic processes were implemented accordingly.

Scholars are investigating on emerging physical treatments using both thermal and non-thermal techniques such as heat-moisture treatment (HMT),^{21,22} cold plasma,⁹ ozonation,²³ irradiation,²⁴ high hydrostatic pressure (HHP),¹⁰ autoclave-cooling²⁵ and ultrasound²⁶ for effectively modifying starch at room temperature and to enhance the functional characteristics of AS. Thus, the properties of the AS can improve in stability, rheology properties, and adaptability to their specific application. Some other technique such as explosion puffing treatment has the potential to promote V-type crystallinity and lower the melting enthalpy of starch double helices. It was at 0.4 MPa that the maximum V-type crystallinity (24.7%) was achieved.²⁷ Furthermore, V-type carriers ordered structure and capacity to load and regulate thymol molecules were impacted by the starch degradation mechanism.²⁸ Despite this, a major factor in determining the quality of food based on starch is starch retrogradation. Its precise evaluation is essential for maximizing food compositions and processing methods in order to preserve the intended level of food quality.²⁹

These changes can improve the rheological dynamics, stability, and overall usability of AS for serving in variety of specific purposes in food applications. Innovative analytical methodologies, including differential scanning calorimetry (DSC), scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), and X-ray Diffraction (XRD), are used to characterize its thermal, morphological, and techno-functional properties. These analyses give good insight into the behavior of AS in different applications, revealing its potential to perform as a versatile ingredient in various systems.^{1,9,23} Popularly, AS has been used in food industries as thickening, gelling, and stabilizing agent in cakes, soups, sauces, etc. Moreover, it serves as an excipient in pharmaceutical formulations, acting as a binder in tablet production and aiding in the controlled release of active ingredients.³⁰ Because of its gluten free property, it can be utilized as a bread ingredient owing to new product development.⁶

Dry and wet extraction methods are typically used method for the extraction of starch. The wet extraction method for starch production generally yields better quality and greater purity compared to dry techniques. This is primarily because dry methods often result in significant damage to starch granules, whereas wet processing allows for effective removal of impurities through water washing. However, the choice of extraction method is influenced by several factors, including consumer and industrial demand, the availability of resources, and considerations related to yield and quality. Additionally, various economic aspects play a crucial role in determining the most suitable approach for starch extraction.³¹ Recently, Harni et al.³² used an emerging non-thermal technique, microwave assisted extraction using electromagnetic waves instead of heat to isolate the starch. Additionally, they investigated on extracting the AS from tubers using 400 W microwave operated for 4 min at 49.2°C and

modified it through cross-linking and esterification and found the best treatment condition that provide the bioactivity of botanical dyes and their functional characteristics upon incorporation with AS that is modified chemically. Furthermore, Damat et al.²⁵ have modified the AS using gelatinize-retrograde technique. Essentially, the arrowroot was immersed at 20% w/w DW and heated at 70°C (10 min) until homogeneity. Then, the starch was autoclaved (121°C) for 60 min and was cooled for 1 h in room temperature. Followed by retrogradation at 4°C for 24 h in freezer, dried, and packed at propylene.

Consequently, no literature is found on comprehensive study on AS isolation, characterization, modification, and application. Therefore, the present study discusses the recent advancement techniques to modify native AS using thermal as well as non-thermal methods and compares that how these treatments alter their physical, chemical, morphological, and structural characteristics in native and modified AS. Besides, the present study also includes application of AS in food industries.

2 | CURRENT PRODUCTION SCENARIO AND NUTRITIONAL VALUE OF NATIVE ARROWROOT

The production and cultivation of AS can be seen predominantly in Indonesia, Brazil, China, Sri Lanka, and in southern parts of India. No reports were found for the current production and cultivation status statistically. However, a limited study reported that the global organic arrowroot market was valued at approximately \$267 million in 2023 and is projected to experience steady growth, reaching around \$375.5 million by 2030. This growth represents an average annual increase of 5.2% from 2024 to 2030.³³ In terms of cultivation, arrowroot is grown on about 365 ha in India, with Thiruvananthapuram leading production at 99 ha, followed closely by Palakkad at 98 ha, and Kollam at 41 ha. Additionally, agricultural statistics from the 2020–2021 period indicate that approximately 120,000 metric tonnes of arrowroot are harvested primarily in regions such as Midnapore, Purbi Medinipur, Ganjam, and Puri in Orissa.³⁴

The proximate composition of AS conducted by different researchers is shown in Table 1. The study conducted by Malki et al.¹ on arrowroot rhizomes which were harvested in five different geographic locations of Sri Lanka. They reported that the crude fat and protein content as 0.26% and 0.72% and those values were

consistent with the findings reported in previous studies,^{36,37} which indicate that the crude fat content of AS varies from 0.12% to 1.0% whereas the crude protein content ranges between 0.4% and 0.8%, respectively. However, another study by Sholichah et al.²⁴ reported a significant increase in protein and fat content of 5.96%–10.8% and 0.90%–1.32%, respectively. This may be because of change in geographic location and variety of arrowroot. According to Nogueira et al.³⁷ lower levels of crude fat and protein are indicators of the starch's purity and quality. The moisture content of the starch is 10.87% which was within the acceptable level (<15%) as reported by,^{1,38} whereas 92.40% is the total solid content. The ash content of AS (1.12%) was similar to values reported in previous studies,^{37,39} which range from 0.16% to 1.5%. The content of ash in starches reflects the presence of mineral compounds such as sodium (52.60 mg/kg), potassium (4312.95 mg/kg), calcium (382.67 mg/kg), and magnesium. Additionally, they had also reported the zinc and iron content to be 2.59 mg/kg and 9.07 mg/kg, respectively. Lower ash content improves starch quality by indicating the absence of inorganic matter, whereas higher ash content suggests a richer nutritional profile.³⁴ Aprianita et al.³⁸ compared the protein, total starch, and moisture content of arrowroot with taro, yam, canna, konjac, sweet potato, and cassava that is grown and cultivated in Indonesia. They found that the protein content of AS is similar as taro and yam (0.60%) which is inferior to konjac (1.2%) and canna (0.80%), however, superior to sweet potato (0.5%) and cassava (0.4%). The total starch content of arrowroot was reported as 84.20%, higher than taro (75.40%), yam (82.10), and konjac (82.40%) but lesser than canna (88.10%) and cassava (85.50%). The moisture content of arrowroot, yam, sweet potato, and konjac is approximately in the range of 10%–12% and the taro and cassava have moisture in the range of 9%–10%. Another study by Sholichah et al.²⁴ on five different accessions of arrowroot cultivated in Indonesia, exhibited the flour amylose content in the range of 26.70%–28.50%.

The moisture content of all arrowroot flour ranged 5.02%–6.53%. Ash, protein, lipid, and carbohydrate content were ranged as 1.38%–1.55%, 5.96%–10.86%, 0.90%–1.32%, and 86.44%–91.65%, respectively. The amylose and amylopectin were approximately in the range of 27%–29% and 26%–41%. Furthermore, Leonel et al.³⁵ prepared a phosphate starch by chemically modifying the arrowroot grown in Brazil. Prior to the chemical modification, proximate analysis such as moisture, ash, protein, fiber, fat, total sugar, and starch of cassava, sweet potato, and arrowroot were investigated. It was found that the moisture (g/100 g) of arrowroot is 11.26, which is inferior to

TABLE 1 Proximate composition of native arrowroot starch.

Samples by region	Crude fat (%)	Protein (%)	Moisture (%)	References
Arrowroot-SR	0.26	0.72	10.87	1
Arrowroot-ID	-	0.60	10.2	24
Arrowroot-BR	0.17	0.19	11.26	35
Arrowroot-ID	-	-	13.13	5

Abbreviations: BR, Brazil; ID, Indonesia; SR, Sri Lanka.

sweet potato (11.95) and cassava (12.69/100 g). The ash and fat content of arrowroot is 0.17%, which is superior than sweet potato (0.12% and 0.13%) and cassava (0.01% and 0.09%). However, the protein and fiber of arrowroot were 0.19% and 0.26% which were inferior to sweet potato 0.26% and 0.16%, and cassava 0.24% and 0.35%. The starch content of arrowroot is 87.44% which is slightly higher than sweet potato and cassava which were approximately 87%. Meanwhile, Ariyantoro et al.⁵ has studied the moisture and amylose content of native and chemically modified AS. They found that the moisture level increased from 13.13% to 13.77% (wb) when the acetylated starch concentration and soaking time increases from 1% to 3% and 30–60 min, respectively. Similarly, the amylose content also increased from 25.52% to 32.21% as the concentration and soaking time of acetylated starch increases.

Arrowroot tuber contains a variety of functional active ingredients such as alkaloids, phenolic compounds (polyphenols), flavonoids, tannins, saponins, and terpenoids⁴⁰ beyond their abundant starch content. Peurarin is one such isoflavones, a sub class of flavonoids that contains anti-oxidative properties which lowers reactive oxygen species and free radicals as well.⁴¹ The HPLC analysis by Lee and Park⁴² found that the average concentration of peurarin in 13 wild arrowroot species from Korea was 1.31 mg/g of dry weight. Plants contain a wide variety of antioxidant chemicals, but the most abundant class is phenolics. The antioxidant capabilities of the bioactive phenolic compounds contained in arrowroot tubers were documented in a study by Octavia et al.⁴³ at a concentration of 0.15/

100 g. According to leamkheng et al.⁴⁴ arrowroot contains a number of recognized phenolic acids, including syringic acid, chlorogenic acid, and protocatechuic acid. Derivatives of kaempferol, quercetin, luteolin, and rutin are among the flavonoids that were identified along with quercetin and rutin which have powerful anti-inflammatory and antioxidant benefits in laboratory studies.⁴⁵ Some research suggests that arrowroot saponins, which are steroidal saponins, may have anti-inflammatory, antioxidant, and anticancer effects. Arunachalam et al.⁴⁰ investigations have shown that arrowroot extracts have extensive bioactivity, including antioxidant, anti-inflammatory, and antibacterial activities.

3 | ISOLATION OF AS

The extraction of AS involves several steps (see Figure 1) to ensure high purity and yield. Initially, the rhizomes were cleaned with tap water to remove debris, soil, and particulate impurities, sliced and peeled, followed by mechanical grinding using a high-speed stainless-steel blender with water for 5 min in a ratio of 1:2 (w/v) for homogeneity to create slurry. The slurry was then filtered using double layered cotton cloth and the water was allowed to separate manually by standing it overnight. This was then allowed to oven dry at 60°C for 8–10 h. The resulting pellets were grounded, sieved, and stored at –18°C in LDPE bags for further analysis.¹ Moreover, Astuti et al.¹⁹ followed similar preliminary steps as Malki et al.,¹ washing, peeling,

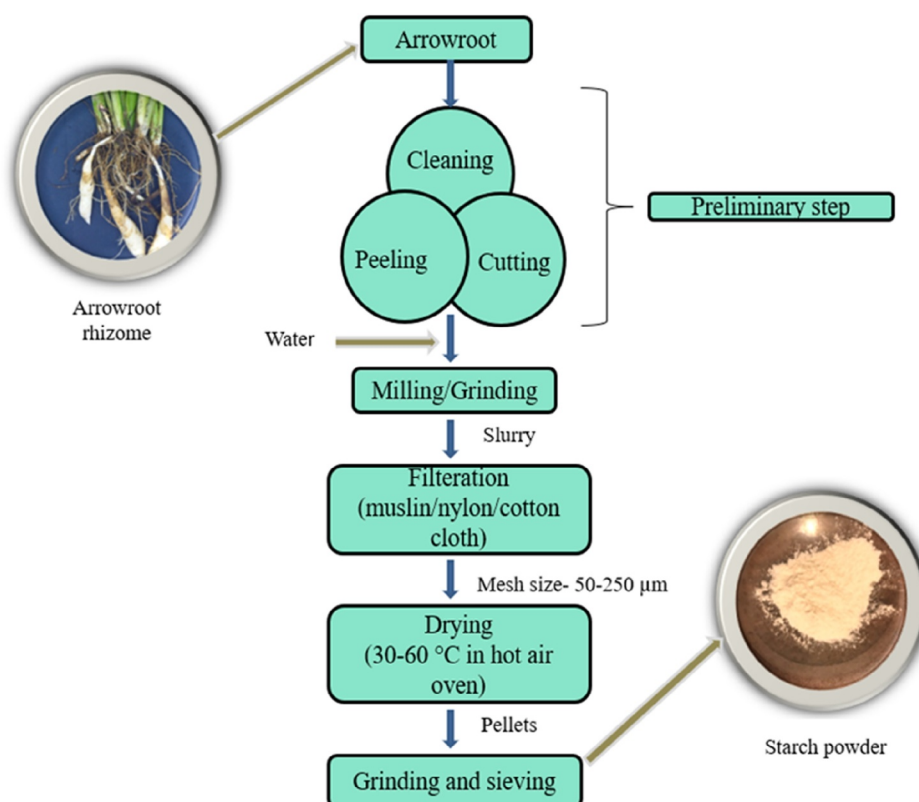


FIGURE 1 A flowchart outlining the key steps involved in extracting starch from arrowroot.

cutting, and grinding. Followed by, immediately suspending in water ratio (1:3.5 w/v) and by using a nylon cloth the slurry was filtered, whereas the filtrate was precipitated. At 50°C the precipitate, which consisted of starch, was dried in an oven to remove moisture. Once dried, the resulting white starch was blended to achieve a uniform consistency. Following this, the homogenized starch was filtered using a 100 µm sieve to ensure a smooth and refined product. Furthermore, Widaningrum et al.⁴⁶ used the same method followed by¹⁹ where; the starch after being extracted successfully was packed and stored in a refrigerator at temperatures ranging from 4°C to 10°C for further treatments.

Moreover, Sholichah et al.²⁴ had successfully extracted arrowroot rhizomes grown in 5 different parts of Indonesia which were peeled, washed, sliced, and immersed in 1000 ppm of sodium metabisulphite solution for 15 min. Then, it was grounded and sieved with 150 µm. It was then packed in plastic bags and stored at room temperature prior to analysis, demonstrating a higher irradiation dose produces brighter arrow root flour. Furthermore, Harni et al.³² successfully extracted the starch using microwave operating where the temperature was controlled using a thermometer. The ratio of water to arrowroot was taken as 33.81:1 g/mL. After extraction, it was filtered using a filter cloth and the resultant were then deposited for 20 h. The precipitate was then dried and pounded using a mortar and pestle. The results of the dry starch were then sieved with a size of 60 mesh. The extracted starch that includes water holding capacity (WHC), oil holding capacity (OHC), solubility, and swelling was then analyzed. Furthermore, Aprianita et al.³⁸ extracted starch from arrowroot (*Marantha arundinaceae* var. Creole), initially the roots and tubers were washed, peeled, diced into cubes, and sliced into dense chips. These pieces were dried in an oven for 40 h at 30°C until they reach a final moisture content of roughly 13%. Once dried, the chips are ground into flour, and any coarse materials are removed by sifting through a 300 µm sieve. To isolate the starch, 100 g of the sieved arrowroot flour is suspended in 300 mL of a 0.075% sodium metabisulphite solution and stored overnight at 4°C. The resulting dispersion was then passed through an aperture size of 150 µm sieve, and the same sodium metabisulphite solution was used to wash the residue. The slurry was allowed to settle at 4°C overnight before being centrifuged at 14,000g for 20 min, after which the free water was discarded. The colored layer that forms were carefully separated from the starch. After the final centrifugation, decanting of supernatant was done, and a 0.1 M sodium hydroxide solution was added to the remaining starch sediment. Distilled water was used to wash the starch pellets until their pH reaches neutral levels. Finally, the recovered starch was dried in an air oven for 30 h at 35°C, ground again, and sifted through an aperture of 250 µm to achieve the desired consistency.

Industrially, to enhance output and processing efficiency, many mechanized stages are used in the industrial-scale extraction of starch from arrowroot. The rhizomes are washed and sliced in rotary or drum washers that can achieve a cleaning efficiency of up to 97% and can handle 200–300 kg/h. Hammer mills or multi-crop extruders are used to grind the cleaned rhizomes, which can extract starch and

juice to a maximum of 86.9%.⁴⁷ The starch slurry is passed through rotary sieves or decanter centrifuges to separate the fibers after grinding. According to Branco et al.⁴⁸ industrial centrifuges may attain concentrations of 20%–35% solids, in contrast to manual screening, which produces starch suspensions with a low solids content (~1%–6%). Using basket centrifuges or filter presses to further dewater the starch-rich slurry can cut drying time in half, or about 4 h. Compared to yields from traditional manual methods (10%–13%), automated conditions typically extract about 12%–14% starch by weight from fresh rhizomes.⁴⁷ With the right mechanical configuration, yields can improve by 16%–20%, which is almost the maximum starch content that a crop can have. In comparison to more conventional approaches automated extraction is noticeably more consistent, faster, and more scalable.

4 | MODIFICATION OF AS

The changes in the starch molecular structure that occur because of various processing, operational and environmental factors are known as modification. These modifications can cause either negative or positive effects on the functionality and structure of starch. Native starches acquired from numerous plants are considered to have varied functions and structure. To improve the functional and structural quality of these starches and achieve more favorable outcomes in various implementations, researchers recommend various alterations in their configuration. Studies were revealed on the enhancement of functional capability of starch by chemical, physical, and mechanical modifications.^{49–51} Despite that, some processing and environmental factors may limit the starch functionality by several alterations during processing and storage.⁵² In contrast to chemical modifications, physical modifications are considered to be preferable and safe as the former incorporate the changes in the chemical configuration of the molecule which limit its use in most of the implementations.⁵³ Table 2 depicts various physical, chemical, and enzymatic modification techniques used in the alteration of AS.

4.1 | Physical techniques

Physical modifications of starch involve changes in its structure and morphology due to various physical factors such as milling, moisture content, temperature, pressure, pH levels, radiation, pulsed electric fields (PEFs), and ultrasonic waves. These modifications lead to alterations in particle size and surface characteristics, as well as changes in solubility and functional properties. Key functional properties affected include water absorption, swelling capacity, and the ability to paste and gel. As a result of these physical changes, the functional quality of modified starch is enhanced, making it more suitable for a range of applications in nutrition, pharmaceuticals, and industrial formulations. The modifications not only impact the physical characteristics of starch but also its performance in different environments, thereby broadening its applicability across various

TABLE 2 Physical, chemical, and enzymatic modifications of arrowroot starch.

Modification methods	Treatment condition	References
Microwave	400 W for 4 min	32
HHP	400 MPa/25–50°C for 15 or 25 min	10
Cold plasma	190,210,230 V for 5–15 min	9
Ultrasound	300/600/900 W for 15 and 30 min	7
Enzymatic techniques	Alpha amylase	54
Hydroxypropylation	STMP/STPP mixture; 7.5–120 min	18
Hydroxypropylation and crosslinking	Propylene oxide (8%, 10%, and 12%); STMP (1%, 2%, and 3%); and STPP (4%, 5%, 6%)	17
HMT + OSA	Moisture adjusted to 30% 100°C for 8 h; 3% OSA	22

Abbreviations: HHP, high hydrostatic pressure; HMT, heat moisture treatment; OSA, octenylsuccinylation; STMP, sodium trimetaphosphate; STPP, sodium tripolyphosphate.

sectors. In contrast to chemical techniques, physical modifications are often viewed as simpler, safer, and more cost-effective. Table 2 depicts various chemical; physical and enzymatic modification used in the alteration of AS. In general, physical modifications can be categorized into two main groups: thermal and non-thermal methods. Thermal modification includes processes such as pre-gelatinization, extrusion, HMT, annealing, and microwave treatments. On the other hand, non-thermal methods encompass applications such as ultra-high pressure, ultrasonication, and PEFs.⁵⁵

4.1.1 | Heat moisture treatment

HMT is a hydrothermal modification method that involves exposing starch granules to low moisture levels (below 35% w/w) and heating them to temperatures above their glass transition temperature (T_g), but below the onset temperature (T_o) of gelatinization, for a set period of time.⁵⁶ This method notably influences crystallinity, morphology, double-helix structure, and amylose-lipid complexes in starch by increasing starch chain interaction, leading to a rearrangement and restructuring of the double-helix formations and refining the smaller crystalline areas within the starch granule,⁵⁷ resulting in changes from native to modified starch's pasting, in vitro digestibility and gel properties.⁵⁸

To assess the pasting and physicochemical properties of AS Marta et al.²² applied single and dual modifications, specifically HMT and octenylsuccinylation (OSA), to assess changes in morphology and functional characteristics of granules. Essentially, the starch was prepared by allowing the moisture content of arrowroot to reach 30% using deionized water, and then equilibrated for 24 h in

refrigerator at 4°C. After equilibration, the starch was heated for 8 h at 100°C followed by drying at 50°C in oven for 24 h and finally grounded and sieved through an aperture of 100-mesh hence, the name, heat-moisture treated starch. For the preparation of OSA starch, the pH was adjusted to pH 8 using sodium hydroxide (1M) after adjusting the moisture content to 30%. 3% solution of OSA was added. The solution was stirred for 3 h to initiate esterification. While in the process of modification, the pH was balanced in the range of 8.5–8.0 using sodium hydroxide and hydrochloric acid (HCl) (both 1M). Post reaction, using HCl (1 M) the pH of the suspension was adjusted to pH 6.5. At 5000 rpm the starch suspension was centrifuged for 2–3 min. The sediment was then washed using de ionized water and again it was centrifuged. After centrifugation, the starch was dried using an oven for 24 h at 50°C. Using an aperture size of 100 mesh sieve, the dried starch was sieved after being grounded. Overall, HMT was found to enhance thermal stability and retrogradation ability, whereas both modifications affected viscosity and absorption capacities (water and oil) differently.

Another study by Tarazi-Riess et al.²¹ treated the native starch using HMT by initially adjusting the moisture content from 12.8% to 25%, adding distilled water. After adjustment of starch, the HMT was performed in a forced air oven at varying time (h)–temperature (°C) conditions: 1/2–120, 1–100, and 16–80. For the preparation of acid and heat-moisture treated starch, 0.2–0.6 M solutions of citric acid are prepared with moisture levels adjusted to 25% in capped glasses. After equilibration, the sample is heated for 8 h at 80°C. Following treatment, the sample were neutralized to pH 7 using NaOH (1M) and then washed thoroughly using distilled water. It was then recovered by centrifuging at 10,000g for 30 min and dried for 24 h at 40°C. The study revealed that both treatments considerably affected the regions of amorphous and crystalline balance. Alterations in shape, thermal properties, and particle size were also studied, which could impact the longevity and functional qualities of AS in different food applications. Furthermore, it is also found that the treatments lower the marker of gut health bacteria, *Firmicutes* to *Bacteroidetes* ratio, indicates a notable increase in beneficial gut bacteria, *Roseburia*. Using HMT and treatment using citric acid techniques to process AS can boost its resistant starch (RS) content, improve its effects on blood sugar, and positively shape gut microbiota, offering potential benefits for gut health and overall metabolic wellness.

4.1.2 | Microwave treatment (have to do)

Microwave treatment generates dielectric heating, causing certain areas of starch granules to heat unevenly. This uneven heating creates localized stress points, resulting in structural breakdown.^{59,60} The effect is particularly pronounced at elevated wattage, which leads to greater disruption of the granules.⁴⁶ Microwave treatment leads to rapid gelatinization and can effectively alter the molecular structure of AS. This method enhances its pasting properties, making it suitable for applications requiring quick thickening. Sriamornsak et al.⁶¹ studied the microwave-assisted modification of AS for making

pharmaceutical matrix tablets and found that when the starch was subjected to high microwave power, high water content for a long time of heating, it led to encouraging characteristics as hydrophilic matrix excipients for tablets designed for sustained release. However, more studies are needed to fully understand its long-term effects on starch functionality.¹⁹ Another study by Harni et al.³² has also used microwave for the extraction of AS and found that arrowroot contains some important polyphenols that acts as antioxidants. Moreover, the study revealed that highest functional data observed at treatment coded as E that is 4 min extraction time, namely solubility, oil absorption, water absorption, and solubility.

4.1.3 | Autoclave treatment

Autoclaving refers to the use of high-pressure steam to modify starch. This technique can effectively gelatinize starch granules, improving their solubility and viscosity. Autoclaving is often combined with other treatments to optimize the functional properties of AS.⁶² Astuti et al.¹⁹ studied the impact of HCl hydrolysis, autoclaving followed by cooling (15 min at 121°C and then cooled for 24 h at 4°C), and conjunction of HCl hydrolysis and autoclaving at two different cooling durations (4°C for either 24 or 72 h) was examined to assess the pasting behavior, functional properties and granular morphology of AS. The study revealed that various physical alterations employed to starch could not significantly enhance its content of RS. Unlike the RS levels, acid hydrolysis (AH) positively influenced the gel strength and solubility of starch while preserving the integrity of its granule structure. Conversely, methods such as autoclaving followed by cooling, as well as their combination with AH, resulted in a reduction of gel hardness but an increase in the WHC of the modified starches, which exhibited deformed granules. Damat et al.²⁵ found that modified AS improves cake quality, offering optimal functional characteristics. It resulted in higher RS 59.28% and carbohydrate levels 25.85%, along with reduced hardness, expansion volume, and ash content. This suggests that modified AS can be a valuable ingredient for enhancing the functional qualities of cakes.

4.1.4 | HHP treatment

This technique combines high pressure between 100 and 1000 MPa, along with temperatures between 0°C and 120°C, to modify the properties of starch. By utilizing this combination of pressure and temperature, significant changes occur in the gelatinization behavior and functional characteristics of starches. These modifications enhance the versatility of starches, making them more suitable for various food processing applications. The process effectively alters the molecular structure of starch, leading to improved solubility, viscosity, and texture. As a result, starches can be tailored to meet specific requirements in food products, such as sauces, baked goods, and dairy items. This means that food manufacturers can create products with enhanced stability and improved sensory qualities.

Moreover, the ability to modify starch properties through this technique opens up new possibilities for innovation in food formulation. It allows for the development of healthier options by reducing the need for additives or emulsifiers while maintaining desirable textures and flavors. Overall, this approach not only improves the functionality of starches but also contributes to more sustainable and efficient food processing practices.⁶³ Oliveira et al.¹⁰ revealed that when HHP was combined with 50°C, the relative crystallinity and the enthalpy of gelatinization has reduced from 6.81% to 35.74% and between 61.3 and 80.3°C because of the severity of treatment temperature. Moreover, it has also demonstrated that thermally assisted HHP has advantages with a potential to be a clean label ingredient that can be applied in producing novel food product. However, more studies are required to analyze its effects on AS's physicochemical properties.

4.1.5 | Cold plasma treatment

Cold plasma technology is an innovative non-thermal method that effectively modifies starch as well as application in various food systems in an environmentally friendly manner.^{64,65} This technique induces both physical and chemical alterations in the starch's molecular structure, enhancing its functional characteristics.⁶⁶ By utilizing cold plasma treatment, cross-linking can occur within the starch molecules, leading to significant changes in their mechanical and rheological properties. The application of cold plasma opens up exciting possibilities for the precise modification of starch, allowing for the development of products with tailored functional properties. This approach not only improves the performance of starch in various applications but also paves the way for innovative product development in food processing and other industries. Overall, cold plasma technology represents a promising avenue for enhancing the versatility and quality of starch-based products.⁶⁷ Atmospheric pressure pin-to-plate cold plasma technique, a novel method studied by Devi et al.⁹ modified the AS by giving treatments: 190–230 V for 5–15 min revealed that the molecular weight of the AS was increased demonstrating cross-linking phenomenon which was also reflected in higher peak viscosity of the starch pastes. An increase in oil and water binding, swelling power, percentage crystallinity, and decrease in pH and paste turbidity has observed.

4.1.6 | Ultrasound treatment

Ultrasound treatment utilizes high-frequency above 20 kHz sound waves to agitate starch suspensions, leading to physical disruption of granules. This can enhance the solubility and swelling capacity of starch, making it more suitable for various food applications. Ultrasound creates cavitation, which leads to the formation of tiny bubbles that can collapse forcefully, producing intense shear forces that break apart the particle size.⁶⁸ As a result, the starch becomes more permeable to water, changing its hydration characteristics.⁶⁹ Fideles

et al.²⁶ explored the technological and physicochemical characteristics of arrowroot flour treated with low-temperature heat and ultrasound, aiming to assess its potential for gluten-free pasta and baked goods formulations and found that it is possible to predict the feasibility of arrowroot flour formulation without gluten. Raza et al.⁷ in their study found that the treated arrowhead tuber using tri-frequency power (300/600/900 W) for 15 and 30 min, showed improved physicochemical properties (solubility, swelling power, OHC, and WHC). Ultrasound treatment led to the deterioration of amorphous areas rich in amylose in the starch granules and a reduction in gelatinization enthalpy (ΔH). This was ascribed to the potential rearrangement of hydrogen bonding within the sonicated starch granules, which resulted from the distortion and disruptions caused by the sonication process.

Additionally, modifications to the AS led to a decrease in the initial gelatinization temperature and a gradual reduction in thermal stability at 270°C. When examining the paste properties, the sonicated samples demonstrated an increased tendency for retrogradation and syneresis, as well as higher final viscosity. In terms of structural changes, a decrease in relative crystallinity was observed, whereas the morphology of the granules was minimally impacted by the ultrasonic treatment.⁷⁰ A recent study investigated the possibility of replacing ultrasonic pasteurization to standard technique used for ice mixes. Additionally, they had also studied on using arrowroot as an alternative stabilizer to commercial stabilizers such as carboxymethylcellulose and guar gum (GG). They found that ice-cream made of arrowroot that has undergone ultrasound pasteurization has exerted significant higher protein, total solids, and free reducing sugars. However, increased overrun and melting was observed when it has compared with ice-creams containing commercial stabilizers.⁷¹

4.1.7 | Pulsed electric field

PEF technology is gaining attention as an innovative, non-thermal method for modifying starch properties such as conformation, microstructure, structural transitions, viscoelasticity, particle size, swelling, solubility, in vitro digestibility, and thermal stability that are essential in understanding its functionality.⁷² PEF technology alters these properties by using high-intensity pulses (>0.1 kV/cm) with micro- to nanosecond durations across electrodes, creating pores in cell membranes. Known for its eco-friendliness, cost-effectiveness, and efficiency, PEF has already been used successfully to modify starch in crops such as potatoes, tapioca, and cassava. However, its effects on AS remain unexplored, presenting a unique opportunity to investigate how PEF might transform AS's physicochemical properties.⁶³

4.2 | Chemical techniques

Chemical modification of starch changes its physicochemical properties by adding new chemical or functional groups while keeping the molecule's shape and size intact. The three reactive hydroxyl groups

on each glucose unit in amylose and amylopectin are the primary sites for these modifications.⁵³ The structure and composition of attached groups, as well as the backbones and side chains, significantly influence the microstructural and behavioral properties of polymers such as starch.⁷³ However, chemical processes typically involve the use of reagents that can pose health risks if residues remain in the food, and they may also harm the environment by producing waste and pollutants.⁷⁴ Various methods can be employed to create starches with specific, desirable traits, including: (a) adding a new functional group to the starch backbone, (b) replacing the hydroxyl group with other functional groups, (c) modifying the distribution of chains or groups along the backbone, and (d) attaching side chains with varying compositions, structures, and lengths.⁷⁵ For the modification of AS chemically, most common techniques used are hydroxypropylation, crosslinking, and succinylation.

Hydroxypropylation introduces hydroxypropyl groups to the starch molecules, improving its water-holding capacity, solubility, and stability under acidic and thermal conditions. Studies have shown that hydroxypropylation enhances freeze-thaw stability and reduces retrogradation, making it ideal for frozen foods.²² A study reported that when sweet potato, arrowroot and cassava starch were modified with sodium trimetaphosphate (STMP)/sodium tripolyphosphate (STPP) mixture with the reaction time varies from 7.5 to 120 min, during which there is an increase in key properties such as starch granule size, solubility, peak viscosity, and swelling power. Additionally, longer reaction times resulted in a reduction in setback for both cassava and AS's. Researchers found that adjusting the reaction time allowed for the production of phosphate-modified tuber starches with distinct characteristics, making them suitable for a wide range of applications in both the food and non-food industries.¹⁸ The cross-linking technique involves adding particular substances to the starch polymer that can react with many hydroxyl groups. By substituting phosphate groups from a mixture of STMP and STPP chemicals for the hydrogen bonds that hold starch chains together, this reaction produces a cross-link bridge using covalent bonds that are more robust and long-lasting.¹⁷ Succinylation is another chemical modification process applied to AS, in which succinyl groups $-CO-CH_2-CH_2-COOH$ are included in its molecular structure. These groups, when introduced to starch it effect the replacement of certain hydroxyl groups with succinyl groups. These introduction of succinyl groups enhance the physicochemical and swelling capabilities, thereby extending its applications in areas such as food and pharmaceutical industries. Succinylation significantly enhances the emulsification properties of starches, reducing their viscosity; hence, they have huge potential in the formulation of stable emulsions and biodegradable films.²⁵

4.3 | Enzymatic techniques

Modification via enzymes is versatile because the types of changes, as well as the kinds of enzymes used, vary widely. A variety of enzymes such as amylases, glucosidases, and transglucosidases offer the possibility of performing a series of reactions such as hydrolysis,

transglycosylation, and branching. In turn, this provides for the extensive range of modified starch products with specific features. Such methodology is flexible enough to work on modified starches from food to pharmaceutical formulations, textile manufacture, and the development of biodegradable materials.⁷⁶ A study by⁵⁴ uses thermostable α -amylase to modify the AS. The researchers showed that AS is suitable for making porous starch because of the high amylose content, A or C-type crystalline structure, and lower relative crystallinity when compared to other tuber starches. Besides, compared with the native starch, the optimized porous AS had improved functional properties of increased adsorption and solubility and reduced swelling power and amylose content. The porous starch was an A-type crystalline structure different from the C_A-type of the native starch, because of the endo-action of α -amylase on starch granules.

5 | EFFECT OF MODIFICATION TECHNIQUE ON NATIVE AND MODIFIED AS PROPERTIES

5.1 | Amylose contents

Based on the amylose content, arrowroot flours can be categorized as high amylose (>24%), intermediate amylose (20%–24%), and low amylose (12%–20%). According to the scholars, arrowroot can be categorized as a “high amylose” flour. The AS has amylose content of 24.95%.¹ A study by Sholichah et al.²⁴ on five different accessions of arrowroot named as A1, A2, A3, A4, and A5 revealed that the amylose content ranged from 26.70% to 28.50% (A1–A5). Another study by Aprianita et al.³⁸ found a relatively less amylose content of 21.9% in *Marantha arundinaceae* var. Creole cultivated in Indonesia.

Marta et al.²² found that the amylose content of starches from Pangandaran, Indonesia, varies among different treatments. Specifically, the native starch has an amylose content of 29.15%, whereas the OSA (octenyl succinate anhydride) modified starch shows a higher content at 33.44%. The HMT starch exhibits the highest amylose level at 36.01%, indicating that both OSA and HMT treatments increase amylose content compared to native starch. Additionally, the study revealed that the amylose levels in OSA + HMT

and HMT + OSA starches as 36.36% and 35.32% in dry basis, respectively. The swelling power is directly proportional to amylose. Higher the amylose content, more the hydrophilic groups will bind water, therefore more the swelling power.³² Astuti et al.¹⁹ bought the arrowroot for their study from the local Indonesian supplier which had amylose content of 25.64%. Table 3 depicts the amylose content of native AS from different geographic locations.

Another study by Leonel et al.¹⁸ found that the native AS of Brazil procured for investigation had an amylose content of 19.66% which profoundly decreases to 4.9% after modification for 120 min. Lowering of amylose content was because of higher amount of phosphorus in starch. Granule size, microstructure, and amylase content determine whether the starch can be procured for gelling, thickening, or stabilizing agent in food industries.⁶⁹ Another study by Ariyantoro et al.⁵ revealed a comparative study on amylose content of native, single, and double acetylated starch as 25.52%, 30.46%, and 30.62%, respectively, in which the acetylated data does not vary much as compared to the former starch. Furthermore, the amylose content of native and porous AS's decreased from 40.76% to 36.56%. The reduction in amylose content due to the action of alpha amylase was reported in other investigations. This is because of the attacks of thermostable enzyme on the amylase chain that consequently release glucose and maltose.⁵⁴

5.2 | Color properties

Color plays a crucial role in determining a product's appeal and perceived quality. From a marketing perspective, appearance significantly influences consumer perception, making it a vital factor in attracting customers and shaping their overall impression of the product. An appealing color can enhance desirability and drive purchasing decisions. For the determination of color, Astuti et al.¹⁹ had used colorimeter to find the L*, a*, b*, and whiteness index. The researcher had revealed that the whiteness index of AH is 96.40% which is superior than both untreated (95%) and acid and autoclave treated AS. On the other hand, the starch undergoing autoclaving and combination of AH and autoclave for 24 and 72 h were in the range 87.15%–91.55% which was inferior than the untreated starch. The

TABLE 3 Physicochemical properties of arrowroot starch.

Sample code	Swelling (g/g or %)	Solubility (%)	WBC (g/g or %)	OHC (g/g or %)	Amylose content (%) approx.	References
AR-Brazil	34.94	42.69			20	18
AR-West Java, Indonesia	868.71	1.26	83.44	103.80	26	19
AR-Indonesia	4.86	81	2.26		26	5
AR-West Java, Indonesia	16.27	9.33	1.13	2.33	29	22
AR-Yogyakarta, Indonesia	7	7.04	76.65	69.62	-	54
AR-India	5.19–9.75	1.07–3.58	2.31	2.60	-	9

Abbreviations: AR, arrowroot; OHC, oil holding capacity; WBC, water binding capacity.

findings indicate that AH, AH-AC (24 h), and AH-AC (72 h) could be effective ingredients for food emulsions. They may be particularly suitable for applications such as soymilk, thickening agents in various liquid foods, lemon curd production, as well as in salad dressings and mayonnaise, where a neutral flavor and low viscosity are desired. The color analysis was also investigated by scholars who were modifying the starch both chemically and heat and moisture treatment. The highest L^* was 96.39, found in OSA starch, however, the HMT starch showed the lowest 94.96. A notable difference in lightness was observed in HMT-modified starch (95.44 and 95.80) which may be due to loss of pigments because of thermal treatment on AS. Meanwhile, for HMT starches—both single HMT and dual modified starches (HMT + OSA or vice versa), the positive values indicate that such starches tend to red. In these cases, thermal treatment resulted in a color shift to red. The yellowness level— b^* in AS (both modified and native) is positive, and it reveals that all types of starch tend to develop a yellowish hue. The HMT starch had the highest b^* value at 4.07, whereas the OSA starch recorded the lowest at 2.13. This suggests that starch treated with heat and moisture has a more pronounced yellow hue compared to OSA starch. Simultaneously, the whiteness index showed a positive relationship with the L^* value, meaning that as the WI increased (such as 95.80 in OSA-modified starch), the L^* value also rose. In contrast, starch modified using HMT, whether through single or dual modifications, exhibited lower WI levels (93.52, 94.51–94.86). The heat and moisture treatment that was applied, lowered the level of lightness in starch.²⁰

Another study by Puspitasari et al.⁷⁷ revealed the L^* value of AS modified with steam-cooling treatments (0–3 cycles) ranged from 80.93 to 93.33. Another study by Sholichah et al.²⁴ revealed that with the increasing dose of gamma radiation (0–5 Gy) the L values of AS increases and vice versa. Moreover, arrowroot flour coded a4b2 (a4-variety and b2-radiation dose) showed the lowest L value of 61.84 and the a5b1 showed the highest value of 80.80 depending on different varieties of AS and irradiation doses which can be considered as an acceptable criterion for flour. The a and b values of different provinces of arrowroot with irradiation doses of 0–5 Gy ranged from 1.47 to 2.47 and 9.22–13.64, respectively. With the increasing doses of irradiation both the parameters increase which indeed has an impact on color parameter. Similar ranges of L^* can be seen in the AS modified with pullulanase enzyme followed by heating and cooling process and combination of these treatments with AH study by Widaningrum et al.⁴⁶ ranged from 87.48 to 92.49.

5.3 | Swelling power and solubility

According to a recent study by Shi et al.,⁷⁸ swelling power describes how well starch can soak up moisture, whereas solubility refers to its capacity to dissipate in water. Nowadays, these two terms are often referred as techno-functional properties which are crucial for determining the end use of the product. The formula used to calculate the swelling power and solubility of the sample can be expressed as follows:

$$\text{Swelling power (g/g)} = \frac{A}{B \times (1 - \text{solubility})}, \quad (1)$$

$$\text{Solubility (\%)} = \frac{C}{B} \times 100, \quad (2)$$

where A is the swollen starch excluding the supernatant, B is the dried sample taken initially, and C is the weight of the dried supernatant. Table 3 depicts the solubility and swelling power of starch derived from arrowroot cultivated in different accessions.

Malki et al.¹ conducted a study on the swelling power and solubility of starch obtained from five different provinces of Sri Lanka and found the swelling power of AS was measured to be 11.22 ± 2.32 g/g, highlighting the ability of starch granules to absorb water and swell. In terms of solubility, AS demonstrated a value of $12.47 \pm 1.62\%$ at 78°C. Ariyantoro et al.⁵ revealed that acetylation also influenced solubility and swelling power. Native starch solubility (0.81%) increased to a range of 0.89%–1.12% following single and double acetylation treatments. The acetyl groups substituted hydroxyl groups, weakening hydrogen bonds, and allowing greater water uptake. Swelling power increased proportionally, with values of 4.86% (native), 7.32% (single acetylated), and 9.30% (double acetylated). The extent of swelling correlated with the acetic acid concentration and immersion time, underscoring the role of acetyl groups in modifying starch granule properties.

Furthermore, study by Devi et al.⁹ discovered that the solubility values varied widely, with cold plasma treatments (190–230 V for 5–15 min) showing up to a 240% increase, presenting new opportunities for applying AS. Solubility ranged from 1.26% to 0.75%, with the highest WSI reported for the 230-15 treatment, increasing progressively to 3.61%, 5.72%, and 6.77% at 70°C, 80°C, and 90°C, respectively. Phosphate modification by Leonel et al.¹⁸ showed increased solubility in arrowroot and cassava starches, though its impact was less pronounced in sweet potato starch. This modification disrupts the strong micellar structure in granules, facilitating water penetration and molecular leaching, thereby enhancing solubility. Cross-linking at low levels further amplified solubility by weakening hydrogen bonds. Comparative solubility values across native and modified starches were: cassava ($43.65 \pm 0.71\%$), sweet potato (38.33%), and native arrowroot (42.69%). Another study by Astuti et al.¹⁹ revealed that the modification process by autoclaving, AH followed by autoclaving for 24 and 72 h preparations significantly reduced the water solubility index (WSI) from 1.26% to 0.35%, 0.72%, and 0.75%, respectively. In contrast, AH notably increased the WSI of AH (1.65%) when compared to the control (1.26%). This phenomenon can be attributed to the hydrolysis of amylose and amylopectin, resulting in shorter chains that enhance solubility. However, the autoclaving-cooling process appears to promote the re-association of these chains, forming tightly packed structures stabilized by hydrogen bonding. Regarding swelling power, the value observed for AC (1016.12%) was comparable to the control (868.71%). This high swelling power negatively correlated with solubility, likely because of alterations in the morphological granule shape and size. AH significantly reduced swelling power to 555.82%.

Other modification techniques studied by Marta et al.²² investigated reduced solubility (9.33%–8.90%) but increased swelling volume in specific cases, namely OSA and HMT–OSA. However, dual HMT–OSA modifications exhibited converse trends in solubility (9.08%) and swelling power (17.66 mL/g in dry basis). Starches with higher molecular weights of amylopectin remained intact, whereas amylose leaching contributed to increased solubility from 8.4% in native starch to 13.7% in ozonated starch (30 cycles).²³ Decreased treatment time in microwave-assisted extraction (MAE) of AS reduced solubility from 91.52% to 85.79%, attributed to lower amylose content and reduced clarity of the starch paste.³² Furthermore, study by Witasari et al.⁵⁴ on modification of AS from native to porous starch discovered that enzymatic treatments, such as those involving α -amylase, significantly enhanced solubility, ranging from 7.04% to 88.92%, compared to non-modified starch. Modified AS exhibited lower swelling properties relative to controls. Reduced swelling power (7.00 to 0.04 g/g) reflected stronger intra-granular binding forces.

5.4 | Pasting properties

It refers, how starch behaves when it is mix with water and then heated or cooked, providing insights into its utility in both food and non-food applications. These attributes include the solubility, swelling, and thickening of starch granules during the gelatinization process. Various modification techniques impact these properties significantly.⁷⁹ Table 4 presents a comparative evaluation of pasting parameters such as pasting temperature and time, setback viscosity, breakdown viscosity, trough viscosity, and peak viscosity of AS. Ariyantoro et al.⁵ revealed that multiple acetylation had the pasting properties include a peak viscosity of 5716 cP, a through viscosity of 2336 cP, a breakdown viscosity of 3380 cP, a final viscosity of 2750 cP, and a setback viscosity of 414 cP. Additionally, the peak time is recorded at 5 min, with a pasting temperature of 70.90°C.

Devi et al.⁹ noted that plasma-treated starch showed an increase in peak and final viscosities compared to untreated starch. However, at the highest voltage (230 V), the final viscosity values were lower than at 210 V. Starches treated with plasma showed improved holding strength, indicating enhanced thermal stability. Astuti et al.¹⁹ reported that modified starches exhibited considerably lower peak

viscosity compared to unmodified starch. Among the treated samples, starch treated with AH followed by autoclaving-cooling (AH–AC for 24 h and AH–AC for 72 h) demonstrated superior thermal and mechanical stability, as reflected by lower breakdown values. AH disrupted the amorphous regions of starch granules, reducing their viscosity and ability to swell. Additionally, autoclaving-cooling treatments significantly reduced the pasting temperature, whereas combined AH and autoclaving-cooling treatments rendered pasting temperatures undetectable.

Marta et al.²² observed that HMT caused a decrease in peak viscosity while increasing pasting temperature when starch was treated at 100°C with 30% moisture content. In contrast, double acetylation modifications produced significantly higher peak viscosity and final viscosity values than native or single acetylated starch, suggesting improved gelatinization properties. Double modifications, such as HMT combined with octenyl succinic anhydride (OSA), resulted in further increases in peak viscosity, final viscosity, and breakdown values compared to single modifications.²² Ozonation, as noted by Handarini et al.²³ led to increased peak viscosity, final viscosity, breakdown, and setback values of AS, whereas holding viscosity decreased. Peak viscosity and final viscosity notably increased with repeated ozonation cycles. Research on irradiated starch showed that the peak viscosity ranged between 3747 and 5352 cP. Flour treated with an irradiation dose of 20 Gy demonstrated the lowest peak viscosity, whereas untreated flour exhibited the highest value. Setback viscosity, a measure of syneresis potential, was highest in arrowroot flour treated with a 20 Gy dose. Higher setback values indicate a greater tendency for starch to undergo syneresis.²⁴ Widaningrum et al.⁴⁶ found that the achievement of peak viscosity during dual modifications such as AH–AC was influenced not just by temperature but also by mechanical stirring. This highlights its suitability for applications in low-viscosity products such as soy milk and chilli sauce.

5.5 | Syneresis due to freeze-thaw stability

Freeze-thaw stability describes how well a substance, such as AS, can retain its structural and functional qualities when subjected to freezing and thawing repeatedly. This stability is evident in the starch's resistance to physical and chemical changes, such as moisture movement, ice crystallization, and retrogradation. The freeze–

TABLE 4 Pasting properties of arrowroot starch.

Sample code	Pasting temperature (°C)	Pasting time (min)	PV	TV	BV	FV	SV	References
AR-Indonesia	68.95	4.53	865	287	578	517	230	5
AR-India	72.6		2149	861.40	1288	1612	323.90	9
AR-Indonesia	78.4	6.93	4477.5	1920.5	2557	3033	1112.5	19
AR-West Java, Indonesia	75.74	-	4857	2119	2738	1087	967	22
AR- West Java, Indonesia	6973	3445	3528	4024	579	-	-	46

Abbreviations: AR, arrowroot; BV, breakdown viscosity; FV, final viscosity; PV, peak viscosity; SV, setback viscosity; TV, trough or holding viscosity.

thaw stability of AS is typically evaluated by measuring physical attributes such as texture, viscosity, and strength of gel resulting from repeated freezing and thawing cycles. In the food industry, freeze-thaw stability plays a vital role in starch-based products, significantly affecting their consistency, overall quality attributes, and longevity. Starches that exhibit strong freezing and thaw stability are particularly in high demand for use in frozen meals, sauces, and various items that experience cycles of freezing and thawing.⁸⁰ According to the findings of Astuti et al.¹⁹ untreated and autoclave-cooling AS had 0% syneresis, AH had 1.99% of percentage syneresis, whereas acid hydrolysis and autoclave cooling (AH-AC) for 24 and 72 h had much higher syneresis than control reaching 77.58% and 123.51%, respectively. Widaningrum et al.⁴⁶ revealed that AH might promote syneresis, whereas the process of autoclaving followed by cooling could help retain it. Starch with greater extensibility tends to exhibit a lower percentage of syneresis. For instance, sample AH-AC 1.3 showed a syneresis percentage of 161.37%, which was slightly lower than the 164.84% observed in sample AC 10.4. However, the difference between these two values was not statistically significant ($p > 0.05$).

5.6 | WHC and OBC

WHC and oil binding capacity (OBC) are functional properties which is an important parameter that shows the starch capacity to retain water or oil. This functional characteristic is crucial when the starch is included in food application that contains water, fat, or oil as ingredients. Astuti et al.¹⁹ revealed AS's when modified had OHC in the range (89.79%–109.01%) and control (103.80%) was not different. Conversely, AH had the lowest WHC of the treated samples, whereas AC, AH-AC 24 and 72 h had the greater WHC than AH and untreated sample. Devi et al.⁹ revealed that the WBC increased ($p < 0.05$) significantly with higher voltage and long-time duration during plasma treatment. Specifically, the combination of increased voltage and exposure time led to a synergistic effect, elevating the WBC in cold plasma-treated AS compared to native samples, which had a baseline of 2.31 g/g. The most notable increase was observed in the sample treated at 230 V for 15 min, showing a rise of 22.5%, whereas the sample treated at 190 V for 5 min exhibited only a 2.16% increase. This increase in WBC is primarily attributed to the modifications on the surface caused by plasma treatment, which enhances the starch's ability to bind water. Additionally, the OBC also rose across all cold plasma treated samples, the highest elevation noted in the 230 V exposed for 15 min sample. Interestingly, variations in input voltage showed minimal changes in OBC when moving from 190 to 210 V; however, elevating the voltage to 230 V resulted in a significant increase of 7.31%–8.46% compared to the untreated sample, which had an OBC of 2.60 g/g. Harni et al.³² showed that WHC increased from 60.29% to 83.98% (MAE = 0–4 min) if the MAE is done for a longer duration. Similarly, OHC found in E treatment (4 min heating) was highest. The WHC and OBC of different varieties of AS are provided in Table 3.

5.7 | Crystalline structure

The term “crystallinity” in relation to starch refers to how starch molecules are organized in a crystalline structure, which influences properties such as gelatinization and digestibility. X-ray diffractometry is used to analyze the crystallinity and type of starch.⁸¹ Starches are classified into three categories based on their crystalline characteristics: A, B, and C-type. B-type starches are identified by a prominent peak around $5.6^\circ 2\theta$ and a broad peak near $23^\circ 2\theta$. In contrast, a distinct double peak at approximately 17° and $18^\circ 2\theta$ showed in A-type starch. A few minor peaks at 5.6° and $15^\circ 2\theta$, together with expansive peaks at about 17° and $23^\circ 2\theta$ can be recognized in C-type. The results from XRD indicated that the starch in question belongs to Type A, with a significant intensity peak at an angle of $2\theta = 19.7^\circ$, which is characteristic of starches containing a complex of amylose and lipid.¹ Similarly, all arrowroot flour exhibited A-type crystalline structure.²⁴ Figure 2 depicts the crystallinity of both modified and native AS. The results indicated that plasma treatment enhanced the crystallinity of AS under all conditions, increasing from 52.99% (untreated) to 56.48% maximum at the condition of 230 kV for 5 min.⁹ The native AS exhibits a reducing sugar content (RC) of 30.96%. In comparison, the RC values for the modified starches are as follows: OSA-modified starch (30.25%), HMT-modified starch (28.26%), HMT–OSA-modified starch (24.88%), and OSA–HMT-modified starch (26.94%). Notably, the HMT-modified starch, whether modified individually or in combination (HMT, HMT + OSA, or vice versa), demonstrates a more significant impact on relative crystallinity compared to the single modification (OSA).²² Starch crystallinity plays a vital role in determining its functionality in food applications. AS possesses unique crystalline structures that influence its gelatinization and retrogradation behavior. Research shows that AS generally has a higher degree of crystallinity compared to other starches such as cassava and maize, contributing to its stability during processing and storage, making it ideal for diverse food applications.⁵³

Moreover, all samples of arrowroot flour demonstrated a crystalline structure of A-type. The crystallinity of both modified and native AS is illustrated in Figure 2. It was found that plasma treatment increased the crystallinity of AS across all conditions, rising from 52.99% in the untreated sample to a maximum of 56.48% at the condition of 230-5. The untreated AS had 30.96% crystallinity. In comparison, modified starches such as HMT, OSA, HMT + OSA, and OSA + HMT exhibited RC values of 28.26%, 30.25%, 24.88%, and 26.94%, respectively. Notably, HMT-modified starches whether in dual modifications (HMT, HMT + OSA, and OSA + HMT) or alone showed a more significant impact on relative crystallinity compared to the single modification by OSA.⁹

5.8 | Functional group and morphology of AS

A study by Malki et al.¹ shows the primary granule shapes of AS in the shapes of irregular globular (21.48%), spherical (28.98%), and

oval (49.54%). The starch granules measured 44.99 μm in length and 31.44 μm in width, with smooth surfaces free from fissures. In another study by Devi et al.,⁹ the morphology of AS was examined before and after plasma treatment at various voltages for up to 15 min. SEM images showed the formation of tiny pores on the starch granules, likely resulting from the extraction process. Plasma treatment also caused surface impressions, indicating plasma-induced etching. Marta et al.²² reported that AS granules were spherical to oval-shaped, with no surface damage following octenyl succinic anhydride (OSA) treatment. However, when treated with HMT, whether in single or combined modifications (HMT, HMT + OSA or vice versa), starch granules showed surface damage, with the granule surfaces becoming rougher because of the development of tiny cracks. Figure 4 shows the morphology of modified and native AS.

FTIR has emerged as a vital technique for analyzing the chemical composition of food items, herbal medicines, and other complex mixtures, providing important information about the functional groups involved. In the realm of verifying the quality and authenticity of herbal medicines, FTIR spectra have gained significant attention from researchers.⁸² The FTIR profile of starch extracted from arrowroot showed absorption bands between 926.97 and 576.99 cm^{-1} , which confirmed the starch, has polysaccharide. A study by Aprianita et al.³⁸ indicated that all five accessions of arrowroot flour exhibited similar spectra, particularly in the broad band region of 3200–3600 cm^{-1} , corresponding to the O-H stretching vibrations of the hydroxyl groups in the glucose monomers of the starch.¹ Figure 3 depicts the FTIR analysis of native AS. Devi et al.⁹ found that starches exposed to intense plasma treatment at temperature-time conditions such as

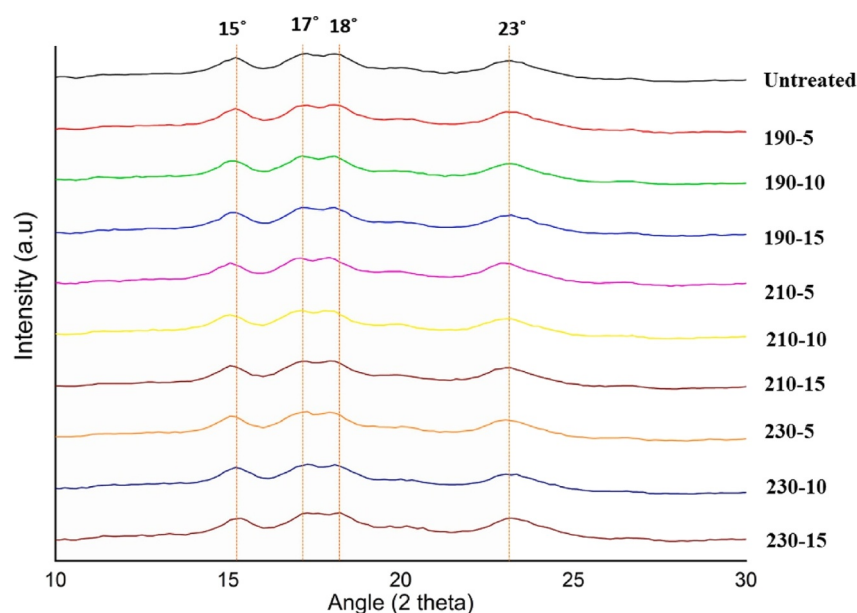


FIGURE 2 X-ray diffractogram of native and modified arrowroot starch (Reprint with Permission from Ref. 9).

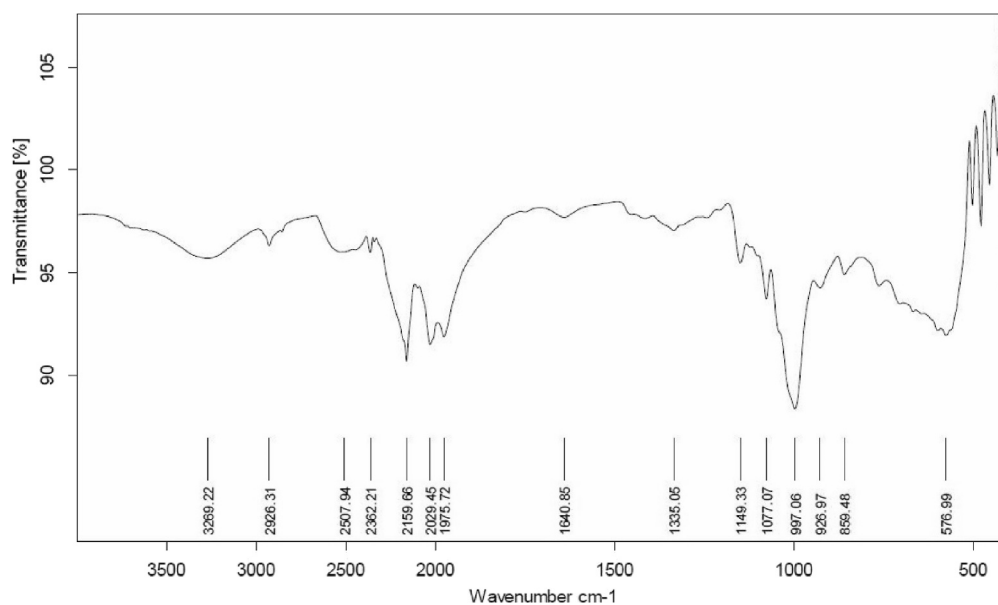


FIGURE 3 FTIR analysis of native arrowroot starch (Reprint with Permission from Ref. 1).

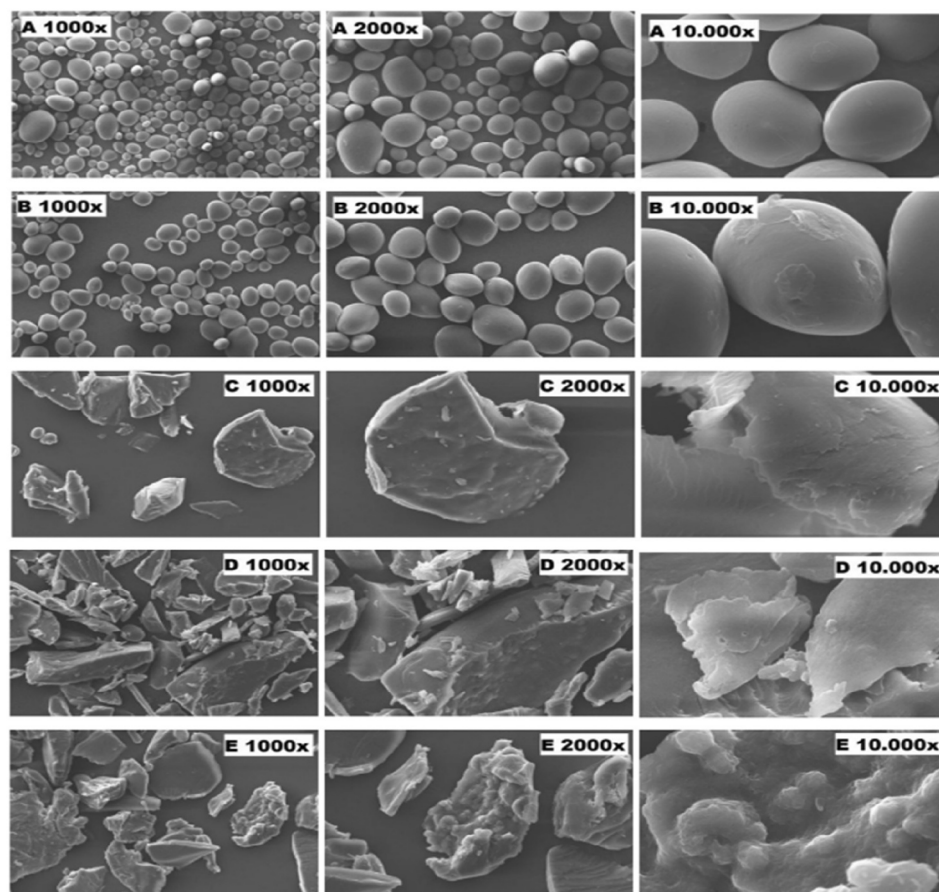


FIGURE 4 Scanning electron microscopic images of native (a), acid hydrolysis treated (b), and autoclave-cooling (c–e) combined AH + AC for 24 and 72 h using magnification of 10,000 $\times$, 2000 $\times$ and 1000 $\times$. (Reprint with Permission from Ref. 19).

190 V–15 min, 230 V–5 min, 210 V–15 min displayed a distinct peak at 1251 cm^{-1} . This peak is ascribed to the amine group, which results from interactions with reactive nitrogen species. Figure 4 presents the FTIR analysis of native AS.

5.9 | MWD of AS

The molecular weight distribution (MWD) of starch is a crucial parameter that reflects the spectrum of molecular weights found in a given sample. This information is vital for understanding the functional properties of starch, as it influences various characteristics such as rheological behavior and gelatinization. Specifically, the particle distribution in AS influences its rheological characteristics and gelatinization dynamics, which are essential for determining its suitability in food applications. To analyze the MWD of starch, techniques such as gel permeation chromatography or size exclusion chromatography are commonly employed. These methods provide insights into the MWD by sorting starch molecules according to their size. Within the food industry, this distribution is instrumental in assessing the role of starch as a binding agent, thickening agent, or viscosity enhancer. Such functions directly impact the stability,

texture, and mouth feel of food products. Understanding the MWD is therefore critical for optimizing starch performance in various food formulations.⁸³ Despite its importance, there has been a lack of studies focused on determining the molecular weight of AS. Consequently, additional research is required to investigate the MWD of both native and modified AS to fully understand its potential applications in food science.

5.10 | Distribution of branch chain lengths in amylopectin

It refers to the variation in the lengths of the branched chains that make up amylopectin, a key component of starch. This distribution is important because it provides an understanding into the structural characteristics of starch molecules. The distribution can be analyzed using techniques such as gel filtration chromatography or molecular sieve chromatography. In starch, the amylopectin chains can be categorized into short, intermediate, and long chain lengths, with each range representing different types of crystallinities: A-type, C-type, and B-type, respectively.⁸⁴ Studies by Witasari et al.,⁵⁴ have shown that treatments such as acid hydrolysis (AA) can reduce the

length of amylopectin chains, shifting them from an intermediate (C-type) to a shorter (A-type) chain length, thus changing the crystallinity of the starch. NS and PS sample displayed relative crystallinity of 29.20% and 28%. Similar findings were reported by⁸⁴ who observed that enzyme treatments, such as bacterial β -amylase and fungal α -amylase, also shorten amylopectin chains in both potato and AS's. Although some studies have explored amylopectin branch chain length distribution in starches, research on AS remains limited. Therefore, further investigations are needed to better understand how the branch chain length distribution in AS affects its properties and potential uses in food applications.

5.11 | In vitro digestibility (RDS, RS, SDS)

In vitro digestibility evaluations classify starch into three categories: rapidly digestible starch (RDS), slowly digestible starch (SDS), and RS. AS exhibits a balanced composition, with moderate amounts of RDS and RS, making it an excellent choice for health-focused food products. The digestibility characteristics of AS are affected by its granular structure and molecular composition.⁸⁵ Studies suggest that treatments such as heat-moisture modification can increase the RS content, offering potential advantages for glycemic management. This digestibility profile makes AS a valuable functional ingredient in developing low-glycemic-index foods.⁶ Taking note of the observations, it can be concluded that various physical alterations made to starch, including AH, did not result in a significant increase in RS content when compared to the control. Treatments such as autoclave cooling and the coupled application of acid hydrolysis and autoclaving-cooling showed minimal changes in RS levels. These findings highlight that RS yield in food is influenced by factors such as the botanical origin of the starch, environmental conditions such as climate and soil, the age of the plant, and the season during which it is harvested.¹⁹ Further, the preparation of RS from AS through

methods such as pullulanase branch chain cutting and a combination of AH with autoclaving-cooling processes yielded lower RS content than the unmodified control. Among these modifications, the AH followed by autoclaving-cooling treatment (1.3 U/g) produced the highest RS3 level (96.25%). However, statistical analyses revealed no significant differences in RS3 levels across the samples (95.71%–95.89%). The lack of increase in RS3 content was attributed to insufficient polymerization of amylose during the modification process. AH alone also failed to enhance the RS3 content.⁴⁶

In another study, HMT and its combination with citric acid were explored under specific conditions (80°C for 16 h; 100°C for 1 h; 120°C for 30 min). Results showed that treatment time, rather than temperature, was a critical factor in elevating RS content, as prolonged treatment at 80°C for 16 h resulted in a more significant increase in RS levels. Conversely, samples treated at 120°C for 30 min exhibited a significant reduction in RS content. The ratio of SDS to RDS was notably higher in samples treated with citric acid or prolonged HMT, suggesting potential benefits such as sustained glycemic control and enhanced delivery of complex carbohydrates to the colon, which may offer broader health advantages in starch-based foods. Figure 5 depicts the in vitro digestibility of both native and modified starch.²¹

6 | APPLICATION OF NATIVE AND MODIFIED AS IN FOOD SYSTEM

AS has become increasingly popular as a versatile ingredient in the food industry because of its unique characteristics. In its native form, AS is widely used as a thickening agent in sauces, gravies, and puddings, delivering excellent gelling properties and a smooth texture when cooked. Its gluten-free nature makes it an essential ingredient in gluten-free baking, where it helps retain moisture and improves the texture of baked goods. Modified AS takes its functionality a step further, with physical or chemical treatments enhancing its

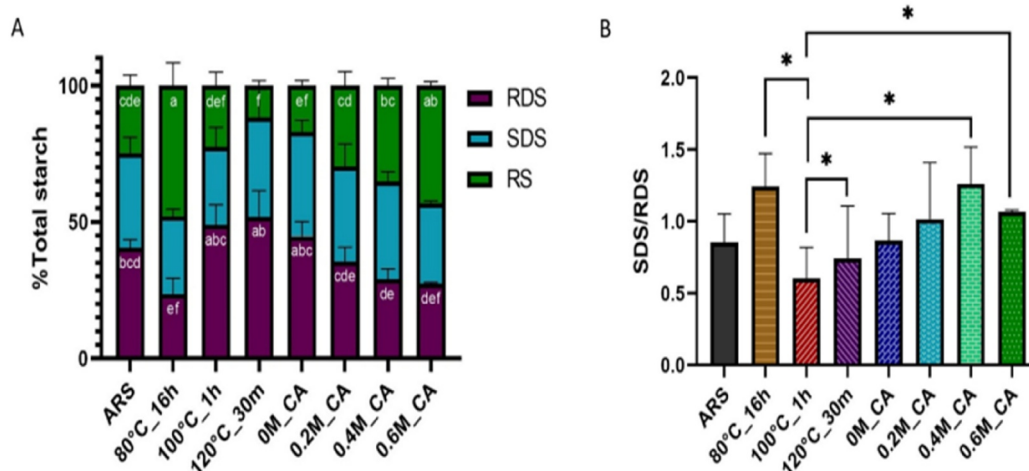


FIGURE 5 (a) RDS, SDS, and RS levels (b) show the ratio of SDS/RDS in native and modified arrowroot starch (Reprint with Permission from Ref. 21). RDS, rapidly digestible starch; RS, resistant starch; and SDS, slowly digestible starch.

performance. AS has shown great promise in the development of bioinks for 3D bioprinting. When combined with GG, it demonstrates excellent potential for forming a cellular framework designed for healing skin injuries. This combination facilitates entrapment and strong intramolecular bonding, enabling the creation of a regenerative bioink. The resulting mesh-like structure possesses water retention, ideal porosity, degradation rate, and mechanical strength, making it suitable for hosting L929 cells with limited toxicity. The engineered pore size allows cells to migrate into the material's bulk while promoting optimal growth and proliferation in multiple focal planes. This innovative 3D printed structural framework made of AS can be considered commonly used and medically safe sugar that can significantly enhance wound healing by fostering cell replenishment in the injured area. Over time, as cells establish themselves, the scaffold naturally degrades without the need for additional surgical interventions. This study highlights the versatility of AS and GG in creating customizable scaffolds. By altering their concentrations or incorporating different cell types, the technology could be adapted to treat a range of injuries. This approach represents a promising step forward in regenerative medicine, combining practicality with effectiveness for improved patient outcomes.⁸⁶

Another study by Cardoso et al.⁶ investigated that when arrowroot was blended with wheat flour the hardness of the bread remained relatively stable when substituting up to 30% of wheat flour with AS, with values ranging from 0.8 to 1.5 N. In contrast, previous studies found that breads made with 20% corn flour, 10% green banana flour, and 25% rice flour exhibited greater crumb hardness compared to the breads in this study that incorporated 40% AS. This indicates that the breads containing 40% AS had lower crumb hardness values than those reported for other composite breads that utilized lower proportions of alternative flours. Moreover, swapping wheat flour with AS did not lead to significant decrease in volume of the resultant bread loaves. Because of the greater gelatinization temperatures of those starches in comparison to wheat starch, delayed gelatinization was observed.

Rohman et al.⁸⁷ revealed that arrowroot tuber can be used for the manufacture of sugar through several stages, namely extraction, hydrolysis, purification, and crystallization. AS granules come in circular, ellipsoid, and oval shapes, varying in size. This starch is characterized by low levels of protein, lipids, and ash, combined with a high amylose content, making it highly desirable for various applications. Its swelling power and water solubility increase significantly at temperatures above 60°C. X-ray diffraction analysis revealed a "C" type crystalline structure, commonly associated with cereals and legumes. The T_g of AS was approximately 120.30°C. Thermogravimetric analysis showed that around 40% of the starch's mass loss, related to depolymerization, occurred between 330°C and 410°C. Starch is widely used in packaging systems as a biodegradable, renewable, and eco-friendly alternative to petroleum-based plastics.^{88,89} AS films were noted for being homogeneous, transparent, odorless, and thicker when prepared with higher starch and glycerol concentrations. The increase in thickness was attributed to the greater amount of dry matter deposited per unit area of the support plate. Water solubility of the films was strongly influenced by glycerol concentration, with higher levels of glycerol

enhancing solubility.³⁷ Given these properties, AS shows significant promise serving as a base ingredient for film production, 3D printing gel, sugar production, and blending agent, offering a versatile and effective solution for various industrial applications. Overall, both native and modified AS's stand out for their ability to enhance texture, stability, and health benefits in food products.

7 | CHALLENGES AND FUTURE ASPECTS

The exploration of AS presents several challenges that must be addressed to optimize its use in food industry and beyond. One significant challenge is the low yield and quality associated with conventional extraction methods. Traditional techniques, which involve cleaning, slicing, and grinding the rhizomes, often result in suboptimal starch recovery because of high granular damage and impurities. This inefficiency necessitates the adoption of innovative extraction technologies such as MAE and ultrasound-assisted extraction which have shown promise in improving both yield and quality. Another challenge lies in the modification of AS to enhance its functional properties. Native starches are prone to issues such as high retrogradation, low thermal stability, and increased paste opacity. While various chemical, physical, and enzymatic modification techniques have been explored, there is a growing consumer demand for "clean" and "green" methods that avoid harmful chemical residues. This necessitates more research into eco-friendly modification techniques that can effectively improve the stability and rheological properties of AS without compromising safety. Moreover, the underutilization of arrowroot in commercial applications poses a significant barrier. Despite its nutritional benefits and potential as a gluten-free alternative, arrowroot remains surpassed by more commonly used starch sources such as potato and cassava. Future research should focus on raising awareness about arrowroot's unique properties and exploring novel applications in various sectors, including pharmaceuticals and cosmetics, to fully leverage its potential. A comprehensive study on the global production and market trends for arrowroot are essential. Current data indicates a growing organic arrowroot market; however, more detailed statistical analyses are needed to inform stakeholders about cultivation practices, yield optimization, and market dynamics. Investigating the genetic diversity of arrowroot cultivars may also lead to improved strains with enhanced starch content and better resistance to environmental stressors. Ultimately, addressing these challenges through innovative extraction methods, eco-friendly modifications, and strategic market positioning will pave the way for broader acceptance and utilization of AS in various industries.

8 | CONCLUSION

In conclusion, this review highlights the significant potential of AS as a versatile ingredient within the food industry and other sectors. The unique characteristics of arrowroot such as its high starch content and gluten-free nature position it as an attractive alternative to more widely used starches such as potato and cassava. However, despite

its promising attributes, the underutilization of arrowroot remains a critical issue that requires concerted efforts from researchers. The challenges highlighted in this study emphasize the importance of adopting innovative strategies in both extraction and modification techniques. By adopting advanced technologies such as microwave-assisted or ultrasound-assisted extraction methods, researchers can enhance yield and quality while minimizing environmental impacts. Furthermore, the shift towards novel green modification strategies using dual modification plasma activated water and cold plasma, PEF aligns with consumer preferences for natural products devoid of harmful chemicals. Future research directions should prioritize comprehensive investigations into the global production landscape of arrowroot. Understanding market trends will not only facilitate better cultivation practices but also drive awareness regarding its nutritional benefits among consumers. Additionally, exploring new applications for modified AS in biodegradable packaging, coating material, pharmaceuticals, or cosmetics could significantly expand its market reach. With continued research efforts focused on innovation and sustainability, arrowroot can emerge as a valuable resource that contributes positively to both health-conscious consumers and diverse industries alike.

AUTHOR CONTRIBUTIONS

Himashri Konch: Writing—original draft; methodology; formal analysis; data curation; resources; investigation. **Rakesh Kumar Gupta:** Conceptualization; investigation; writing—original draft; methodology; validation; visualization; writing—review and editing; software; formal analysis; data curation; resources. **Prem Prakash Srivastav:** Visualization; validation; writing—review and editing; project administration; resources; supervision.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data are included in the manuscript.

ETHICS STATEMENT

This study did not involve animal experiments or human participants and thus ethical approval was not required.

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