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Water Chestnut (*Trapa natans*): Physicochemical Properties of Starch and Industrial Applications across Food, Textile and Pharmaceutical Sectors

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Abstract:

Water chestnut (*Trapa natans*) are full of nutrition, which has drawn the attention of researchers because of their exceptional starch attributes and diverse applications. They are known for their high carbohydrate; dietary and essential minerals content, as well as low caloric profile. Water chestnut take part notably in a balanced diet and are incorporated into different culinary applications globally. The starch from *Trapa natans* shows considerable physicochemical properties, including gelatinization temperature, resistance to retrogradation and superior water-holding capacity, making it a promising constituent for food and non-food industries. In the food sector, water chestnut is used as a thickening agent, stabilizer and texturized in gluten-free products, while its bioactive compounds find applications in functional foods. Beyond the food industry, this starch has potential in the textile and pharmaceutical sectors, providing environment-friendly alternatives for fabric finishing, biodegradable packaging films and excipients in drug formulations. This review provides a comprehensive overview of the nutritional properties of water chestnuts, their physicochemical properties and diverse industrial applications exhibiting their capacity to accelerate product innovation across multiple sectors.

Keywords: Water chestnuts, *Trapa natans*, Starch physiochemical properties, Industrial applications

1. Introduction

Trapa natans L., commonly known as "water chestnut" or "singhara nut," belongs to the family Trapaceae and is referred to as "singhara" or "simkhata" in Hindi, and "karimbolam" or "vankotta-kkaya" in Malayalam. Despite its high nutritional value, water chestnut is underutilized in food processing due to its seasonal availability of only two to three months each year. Globally, it is cultivated on approximately 603,076 acres, yielding a total of 2,327,495 tonnes. The fruits of *Trapa* are known for

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their cooling, diuretic, sweet, astringent, and tonic properties (Patel et al., 2011). Despite their name, water chestnut are not actually nuts. Instead, they are aquatic tuber vegetables that thrive in shallow water bodies, such as lakes, paddy fields, marshes, and ponds. Native to several islands across the Indian and Pacific Oceans, water chestnut are also widely found in regions of Southeast Asia, southern China, Taiwan, Australia, and parts of Africa (Rajput & Singh, 2023).

It is harvested when deep brown, water chestnut have crisp, white flesh enjoyed raw or in Asian dishes like stir-fries and curries (Rajput & Singh, 2023). Water chestnut are mainly regarded as a vegetable and are commonly used in human foods, particularly in sweet dishes and baked goods, often in the form of dried flour (Patel et al., 2010). Raw water chestnut are 74% water, making them a low-calorie option and a good source of fiber, potassium, copper, manganese, vitamin B6, and riboflavin (Rajput & Singh, 2023).

During freeze-thaw cycles, water chestnut starches exhibited greater syneresis and reduced paste clarity over storage time. Some sources demonstrated enhanced swelling power, water-binding capacity, freeze-thaw stability, solubility and viscosity. However, these sources had lower protein levels, pasting temperature, amylose content and gel firmness (Gani et al., 2010). Starch serves as a thickening, bulking, and gelling, stabilizing, and water-retaining agent, widely used in food processing. Both native and modified starches enhance the texture and quality of products, with modified starches now regarded as essential functional food additives (Gani et al., 2010). Water chestnut possess low content of fat, ash and protein and higher carbohydrate content, which make it more efficient and its extraction is starch cost-effective than the starch from other sources. The lowest impurity in water chestnut starch make it a best candidate to be used as a pharmaceutical excipient, used for controlled release-formulations, such as tablets (Kaur et al., 2023). Moreover, its gelling, binding and thickening characteristics prove it to be a useful candidate in paper, biomedical, textile and other commercial applications (Syed et al., 2021). Water chestnut starch stands out for its unique ability to develop a firm, crunchy texture when heated, unlike conventional starches like potato or rice. This property makes it highly beneficial for the food and other related industries. A complete examination of its characteristics could accelerate its industrial applications, with the capacity for exact physicochemical modifications to fulfill particular requirements (Gani et al., 2010). Reviewing the literature, it is acknowledged that water chestnut starch has excellent nutritional profile and wide range of applications across the pharmaceutical, textile and food sectors as indicated in Figure 1:

Figure 1 Applications of water chestnut starch

2. Chemical Composition

Water chestnut provide important minerals, lipids, proteins, carbohydrates and variety of vitamins (A, B, C A, and E). Dietary fibers and polyphenols, including flavonoids, phenolic acids and hydrolysable tannins are also present in it (Patel et al., 2010). A significant amount of phenolic acids, including gallic, ellagic and ferulic acids are present (Aleksic et al., 2018). The primary active compounds in the aquatic fruit extract of water chestnut are phenolics, which have attracted scientific interest due to their potent anti-free radical properties. The high polyphenol content in water chestnut fruit aqueous extract is supported by evidence demonstrating significant in vitro antioxidant activity against free radicals (Corovic et al., 2021).

Table 1 Chemical composition of water chestnut

Component	Percent
Water	80.9
Lipids	0.37
Total ash	1.32
Crude fibre	0.71
Total proteins	1.86
Amylose	29

(Singh et al., 2017; Kaur et al., 2023)

3. Food Applications

Water chestnut fruits can be dried and ground into flour, which is sometimes used as a substitute for arrowroot flour. They are also enjoyed roasted or boiled. With a nutritional profile that includes 16% carbohydrates and 2% protein, these fruits offer substantial nourishment. Raw water chestnut are juicy and crisp, while cooking softens them but keeps their crunchy texture. Water chestnut kernels are highly nutritious, containing a rich array of vitamins, carbohydrates, minerals and essential elements such as iron, manganese, copper, magnesium, sodium, and potassium (Rajput & Singh, 2023). At Wular Lake in India, approximately 4-5 million kilograms of water chestnuts are harvested each year, providing sustenance for nearly 30,000 people over a five-month period. In nations like Bangladesh, China, and India, water chestnuts are widely sold by street vendors, either fresh or cooked. The younger pulp, known as "milky" water chestnut, is enjoyed both raw and cooked, while the mature pulp is typically boiled, dried, and incorporated into various recipes. Besides being consumed as a vegetable, water chestnuts are also used to prepare tea, curries, and flour for breads like chapattis and poories, and are available in dried form as nuts. Nutritionally, water chestnuts are comparable to wheat (Malviya et al., 2010). To cure high blood pressure in pregnant women, the porridge prepared with water chestnut flour is recommended as water chestnut flour accelerates fatal growth. The women having bleeding issue, can utilize dried-seeds to overcome the issue. Moreover, its juice exert several therapeutic uses, including the elimination of bile (Rajput & Singh, 2023). Boiled water chestnut is a common form for consumption, and in India, it is valued for its high nutritional content, making it suitable for premium chapattis and sweets. Increasingly, people across socioeconomic backgrounds globally use this medium-to-low calorie food for snacks due to its rich nutrient profile In developing countries like India, malnutrition remains a recognized issue, which experts have aimed to address through scientific research and novel food formulations derived from various nutritional sources to enhance diets (Sachin Parmar, Amit Gangwal, 2011).

Non-traditional food sources have gained significant interest for their potential as functional ingredients in new food products. The starch characteristics of water chestnut (*Trapa natans*) are shaped by its physicochemical properties, such as mineral composition, growth period, variety, grain size, environmental conditions, and the amylose-to-amylopectin ratio (Mahnoor et al., 2024). It also helps improve food product shelf life and stabilize gels during processing. India's bakery industry, one of the country's largest food sectors, ranks as the world's second-largest biscuit producer after the USA. Given the high prevalence of celiac disease, especially in North India, there is a growing demand for gluten-free products, as these are essential for managing the condition and improving the quality of life for affected individuals. Consequently, gluten-free options are expanding globally in response to the rising celiac diagnosis rates (Kaur et al., 2023)

Water chestnut (*Trapa natans*) is widely used in the Indian subcontinent as a substitute for cereals during fasting and is considered a suitable replacement for wheat flour (WF), especially beneficial for individuals with Celiac disease due to its gluten-free nature (Mir et al., 2015)**.** Additionally, the flour obtained from water chestnut can be added into several food products like noodles and cookies (Choudhury and Chaudhary, 2023). In the same way, mixing wheat and water chestnut flour contributed to the shortening of cooking time of noodles. Moreover, the mixing resulted in the alteration of texture profile and retaining of overall desirability of noodles developed with composite flour than that of traditional wheat flour. These results suggested the huge potential of water chestnut flour to be a potential candidate in the development of novel foods (Hussain et al., 2019). In India, cookies made from water chestnut flour are a popular delicacy during Navratri and other fasting days. Its high fiber content and various nutritional benefits further support its use in food applications. Compared to WF cookies, water chestnut flour cookies show a higher spreading ratio, likely due to WCF's elevated starch content, which has fueled demand for this alternative flour (Singh et al., 2011). Research on modified water chestnut starch revealed its positive influence on sponge cake characteristics; the addition of acetylated starch significantly improved the volume index, while acid-thinned starch at a concentration of 1% w/w enhanced the symmetry index. At a rate of 4–5% w/w, pre-gelatinized and acid-thinned starches achieved a notable uniformity index. In a separate study, yogurt enriched with water chestnut starch was evaluated in comparison to yogurt containing 0.5% w/w gelatin as a stabilizer (Lutfi & Hasnain, 2009)**.** Water chestnut starch improved yogurt's syneresis, water-holding capacity, and viscosity, achieving high sensory acceptance without affecting taste or quality. Optimal results for water-holding capacity, syneresis, and viscosity were observed with water chestnut starch at 1.25% w/w and 0.75% w/w, extending yogurt's shelf-life up to four weeks (Hallale & Jadhao, 2016).

Starches, especially from water chestnut, are crucial in food and industrial applications due to their thickening properties, and are often used to improve texture in foods like sauces and soups. Water chestnut starch has an amylose content of 22.3% w/w, closely linked with amylopectin, although it's generally not applied as a stabilizer in dairy products (Hallale & Jadhao, 2016)**.** However, research indicates that water chestnut starch purified from Trapa bispinosa Roxb contains 7–8% moisture, 0.21–0.22% protein, 0.03–0.04% ash, and 81–85% carbohydrates, delivering 385 calories per 100g. When used in dahi at varied concentrations, water chestnut starch significantly affected dahi's physical, chemical, and sensory qualities, showing excellent stability by reducing syneresis and enhancing creaminess and texture without impacting flavor or quality. Studies further indicate that dahi with added water chestnut starch remained viable for up to one month under cold storage. Additionally, water chestnut starch, both native and modified, serves as an effective fat substitute in mayonnaise, potentially lowering its calorie count. Mayonnaise made with succinylated water chestnut starch showed superior sensory and textural quality over acetylated starch formulations (Ansari et al., 2017).

Biodegradable and edible films are plant-based packaging materials, which are increasingly used to extend the shelf life of food and reduce environmental problems. These materials are being consumed along with the food, which enhance nutritional and sensory attributes of food. Antimicrobial agents are also added to edible films to prevent microbial contaminations on food surfaces (Basch et al., 2013). In this context, water chestnut is exhibiting as a sustainable packaging material for food and non-food uses (Singh et al., 2009). The antimicrobial properties of films prepared with water chestnut starch-chitosan were accelerated with the addition of some additives, including nisin, glycerol monolaurate, *calendula officinalis* extract and pine needle essential oil (Mei et al., 2013)**.** These additives effectively inhibited the growth of *Escherichia coli*, *Staphylococcus aureus*, and *Listeria monocytogenes* across different concentrations. Another study developed a biodegradable film from water chestnut starch and polyvinyl alcohol (PVA), observing that plasticizer additions decreased the swelling power and increased solubility of the films, with lower plasticizer concentrations enhancing tensile strength (Zehra et al., 2022). Additionally, clusteroluminogenic films made from maize, potato, and water chestnut starch revealed that water chestnut films had the highest transmittance. These films maintained consistent clusteroluminescence in fresh and frozen food but showed decreased luminescence after thawing, suggesting potential use as an indicator of storage conditions for frozen foods (Lai & Wong, 2022).

It was investigated the effects of edible coatings made from water chestnut powder on the quality and shelf life of Kala Kullu apples. They tested two coating concentrations: T1 (2% water chestnut powder) and T2 (2.5% water chestnut powder), using 2% guar gum as a positive control and leaving some apples uncoated as a negative control (Mahnoor et al., 2024)**.**

3.1. Physicochemical Properties

The swelling capacity of starch reflects the degree of interaction between its crystalline and amorphous regions. This capability is primarily determined by the granules' water retention, facilitated by hydrogen bonding. During gelatinization, hydrogen bonds that stabilize the double-helix structure of starch crystallites break, allowing new hydrogen bonds to form between exposed OH groups in amylose, amylopectin, and water molecules. Partially decomposed starch granules absorb water more conveniently as compared to whole ones, which enhances their potential to swell. Granule's disintegration and the composition of starch considerably affect swelling along with gelatinization temperatures. Water chestnut starch is recognized for its high swelling capacity, likely attributed to its lower amylose content and a higher proportion of impaired starch granules (Kaur et al., 2023). It was observed this trait within a temperature range of 40 °C to 95 °C, with measurements taken at 5 °C intervals. Notably, swelling ability surged sharply at 50 °C, then continued to rise moderately with increasing temperature until reaching the gelatinization point (Cai et al., 2014). It was found that both annealing and heat moisture treatment reduce starch granule swelling power and solubility, suggesting strong forces within the crystallite regions of modified starches. During annealing, amylose chains shift to helical structures, increasing inter-chain attractions and lowering swelling power. Increased moisture content also enhances interactions in crystalline regions, limiting

Table 2 Comparison analysis of characteristics of water chestnuts, potato and maize starches

Characteristics	Water chestnut starch	Potato starch	Maize starch
Amylose (%)	21.8-32.10	26.8-30	25-28
Swelling (g/g at 90 °C)	1.4-11	51.2	10.9
Solubility (% at 90 °C)	17	13.87	18.7
Water absorption capacity (%)	133.4	125-140	115-130
Gelatinization temperature(°C)	69.60	59.9	68.7

(Kaur at al., 2023; Song et al., 2013; Jansky & Fajardo, 2016; Obadi et al; 2023, Yousif et al., 2012)

swelling. Heating starch suspensions causes granule hydration, swelling, and some solubility. When measured in water chestnut starch, swelling varied by lake source, with Anchar Lake starch showing 1.4% to 11% w/w swelling and Wular Lake 2.2% to 15% w/w, while Dal Lake starch peaked at 4.2–18.3% w/w. Dal Lake samples also showed higher solubility (3.4–17% w/w) compared to other sources. Swelling was limited below 70 °C but increased between 70 °C and 90 °C due to hydrogen bond disruption in amorphous regions (Gani et al., 2010).

Higher amylose content enhances interactions with amylopectin chains, resulting in increased gel shrinkage and syneresis. The syneresis of starch gels can be decreased by increasing the level of acids (Pulgarín et al., 2023). The reduction in starch syneresis during the formation of gel can be reduced by lower amylose. This is due to the low water uptake by starch granules during their breakage and stiffening effect that heat and moisture treatment applies on the granules (Singh et al., 2019). On the other hand, heat and moisture treatment have tendency to increase syneresis than native starch. The increase in the light transmittance of water chestnut starch was observed with the addition of salt, particularly at the concentrations of 0.5% and 1% by w/w. The breakdown of hydrogen bonds within the starch structure and between starch-water molecules improves the transmittance of light. This improvement in transmittance resists the rearrangement of starch during retrogradation. That is why salt-treated starch gels give higher transmittance than untreated native starch gels. Furthermore, retrogradation is significantly reduced by treating water chestnut starch with extrusion polyphenol, which boosts transmittance levels (Lutfi et al., 2019).

The changes in phase are observed from an organized to disordered form when the mixture of starch and water is applied with shear heating at high temperatures of gelatinization. The change in arrangement enhances the viscosity of the mixture, which leads to the formation of starch paste. The length and amount of amylose chains and branching and the size of amylopectin chains are the factors which influence the starch paste (Reddy et al., 2017; Cruz et al., 2013). The physiochemical and morphological properties are changed by repeated freeze-thaw cycles in starch containing foods, including soups, sauces and ice creams. In the start, a consistent starch gel is formed upon gelatinization, but gel becomes disordered due to freezing. Continuous freeze-thaw cycles change into cryotropic gels, conclusively offering the finished products a spongy texture (Gong et al., 2024).

3.2 Comparative analysis of starch characteristics from different sources

The starch originated from water chestnut possess small; uniformity and granular structure as compared with potato starch having exceptional shapes while same in size. It has higher high amylose concentration, which exhibits capacity for the development of resistant starch and digestibility (Dularia et al., 2019). It has considerably significant swelling potential with medium release of water when thawed that exhibits its functionality with some improvement gaps (Alam et al., 2021). A brief comparison of physicochemical properties of starch from different sources is presented in Table 2.

4. Industrial Applications

Starch is a naturally originated glucose homo-polysaccharide of nutritional and industrial significance. The complexity of structure and poor solubility of starch (native) in water reduces its industrial use. The functionality, structure and reactivity of the native structure can be subjected to modification by various methods, including chemical, physical and enzymatic (Nawaz et al., 2020). The water chestnut starch can be modified and processed into various commercial products as shown in Figure 2:

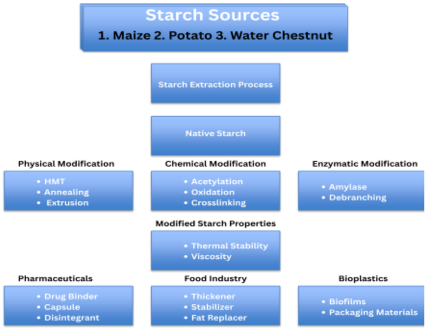

Figure 2 Modification of starch for industrial applications

Starch is one of most searched pharmaceutical ingredients worldwide, famous for its bio-stability, availability, and diverse attributes. The starch collected from maize and potato is used in tablet formation as a binding agent, while research is being carried out to explore alternative botanical sources (Okunlola & Odeku, 2011). Binders have a great role in formulating tablets, which provides crucial adhesion between granular ingredients to make exceptional bonding during compression. Plasticity is increased by the incorporation of binders, which accelerates the rate of compaction and improves the bonding between particles. Furthermore, the risk of brittle fracture during the tablet formulation process by Additionally, the risk of brittle fracture is decreased by the addition of binders (Khairnar et al., 2024). A few industrial applications are shown in Table 3:

Table 3 Application of water chestnut in industrial sector

Industry	Application	Property
Pharmaceutical	Tablet	Binder
Pharmaceutical	Encapsulation	Coating
Plastic	Bioplastics	Binder
Nutraceutical	Nano-capsulation	Coating
Textile	Removal of rhodamine B	Bio-adsorbent

(Rao et al., 2011; Ahmad et al., 2019; Kulkarni & Badwe, 2020; Khan et al., 2013)

5. Processing Limitations and Mitigation Strategies

The processing of water chest of nuts faces various constraints, especially because their high moisture content and sensitivity to spoilage. Water chestnut obtained from freshwater are more susceptible to microbial contamination, which leads to quick deterioration that faces challenges for transport and storage. They need additional processing steps due to their fibrous skin, which is labour intensive and increases processing costs. Furthermore, water chestnut starch is very sensitive to pH and temperature, which can reduce its functionality during processing at industrial scale. Preservation techniques and drying methods are usually applied to retain the quality of the product, however these can be energy-requiring and cost demanding. Resolving these challenges is necessary to enhance the efficiency and cost-effectiveness of water chestnut processing at industrial scale.

Starch extracted from water chestnut have tendency to undergo retrogradation or decomposition when subjected to heat and pH changes. Carboxymethylation, succinylation and acetylation, collectively known as CMS, enhances swelling, paste clarity, resistant start content and solubility, which make it an ideal candidate for food and pharmaceutical industries (Xiao et al., 2018). To improve the stability of water chestnut starch, the pasting temperature is accelerated and viscosity breakdown is reduced during hot processing. Moreover, Packaging films containing water chestnut starch nanoparticles enhanced tensile strength, limited the solubility and transmission through water vapor, which make it more efficient (Dularia et al., 2019). Application of dry heat with alginate can mitigate solubility and swelling but enhanced water absorption and thermal response, which support the controlled release (Lutfi et al., 2021).

6. Conclusion

In conclusion, water chestnuts have notable significance due to their nutritional profile and diverse applications in the food, pharmaceutical and textile industries. Despite this potential, the processing of water chestnuts has considerable limitations; high perishability and microbial spoilage remain basic challenges, often requiring special storage and preservation methods to extend their shelf life. The original form of starch that originated from water chestnut is susceptible to temperature and pH, which obstacles its utilization in various thermal applications. Chemical or physical alterations are mostly crucial to boost solubility, textural and thermal characteristics for industrial applications. However, it dominates over many for its various physiochemical properties. Its cultivation is usually seasonal and regional, which may have an effect on constant supply for commercial applications. Nevertheless, its growth ability in marginal lands makes it a sustainable option. More research studies are required to assess consumer acceptability. Moreover, the peeling process is laborious work which raises its processing costs and limits its usage on a large scale. Additionally, a lack of standardized processing methods for water chestnut-based products cannot maintain consistency and quality in end-products. Addressing these limitations through technological innovations and optimized processing techniques could accelerate the market potential of water chestnuts, making way for the sustainable rise in different sectors.

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