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Gluten-free applications of water chestnut flour in bakery, snacks and traditional foods: A review

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Abstract
Water chestnut (*Trapa* spp.) flour is increasingly recognized as a valuable gluten-free ingredient due to its superior nutritional composition, distinctive starch functionality, and suitability for a range of food processing applications. Its high levels of dietary fiber, resistant starch, phenolic compounds, and essential minerals support health-focused product development, particularly for individuals with celiac disease and gluten intolerance. This review compiles recent advancements in the characterization, processing, modification, and utilization of water chestnut flour in bakery products, snacks, and traditional food systems. Key physicochemical attributes, including water absorption capacity, gelatinization behaviour, and pasting properties, are discussed in relation to dough structure, sensory performance, and storage stability. Emerging technological interventions such as hydrocolloid incorporation, composite flour formulation, and enzymatic modification are highlighted for their role in improving product quality. Challenges involving dough machinability, oxidative deterioration, and post-processing staling are addressed along with future opportunities for commercial expansion and functional food innovation. Water chestnut flour demonstrates significant promise as a sustainable, nutritious, and multifunctional gluten-free ingredient for modern food industries.

Keywords: Water chestnut flour, gluten-free bakery, resistant starch, functional properties, snack products, fasting foods, hydrocolloids, composite flours

Introduction

Growing consumer demand for gluten-free and health-oriented foods has intensified the exploration of alternative flours with superior nutritional and functional properties. Water chestnut (*Trapa* spp.) flour has gained significant attention due to its naturally gluten-free nature and its rich composition of carbohydrates, minerals, and bioactive compounds. Traditionally consumed in various regions of Asia, particularly India, water chestnut kernels are processed into flour that is widely used in fasting foods and cultural dietary practices. Its unique starch profile and mild sweet flavour further support its compatibility with diverse food formulations intended for mainstream consumption.

As consumers move toward clean-label, functional, and minimally processed foods, the need to identify alternative flours beyond conventional cereals has intensified. Water chestnut flour (WCF) exhibits desirable nutritional qualities including high dietary fiber, resistant starch, and low-fat content, making it suitable for health-driven product development. Additionally, its mineral content—particularly calcium, potassium, and iron—enhances its physiological value and supports its positioning as a functional ingredient in specialized diets. These benefits make WCF a promising candidate for gluten-free applications across multiple product categories such as bakery items, extruded snacks, and traditional foods.

Despite its advantages, industrial utilization of WCF encounters challenges primarily related to the absence of gluten, which affects dough elasticity, gas retention, and machinability in leavened bakery products. Variability in flour composition due to seasonal harvesting conditions, processing methods, and particle size also influences product quality and sensory characteristics. Moreover, storage-associated issues such as moisture sensitivity and retro gradation may reduce shelf stability and consumer acceptance over time.

To address these limitations, research efforts have focused on optimizing extraction and milling techniques, incorporating hydrocolloids, and employing composite flour strategies to enhance structural and textural properties in WCF-based foods. This review critically discusses the nutritional relevance, physicochemical characteristics, technological enhancements, and product-specific applications of water chestnut flour, while also outlining future industrial opportunities and research directions for the development of sustainable, high-quality gluten-free food systems.

Nutritional Composition

Water chestnut flour is predominantly composed of carbohydrates (70-72%), with moderate protein (6-8%) and very low fat (0.5-1.2%). It contains a notably higher crude fiber and mineral content than wheat flour, contributing to improved digestive function and micronutrient intake (Singh & Khan, 2022; Priya *et al.*, 2020) [6, 4]. Potassium, calcium, and iron are particularly abundant, supporting electrolyte balance and anaemia prevention.

Starch constitutes approximately 52-55% of the dry weight and includes a significant proportion of resistant starch, contributing to reduced glycaemic response and potential metabolic health benefits. The presence of polyphenolic compounds adds antioxidant functionality, strengthening its role in functional food formulation (Thakur *et al.*, 2019) [7].

Physicochemical and Functional Properties

The functional behaviour of water chestnut flour (WCF) in food matrices is primarily driven by its carbohydrate-rich composition and granule morphology. Its high water absorption capacity supports enhanced dough viscosity and moisture retention, which is particularly important in gluten-free bakery applications where hydration helps compensate for the lack of gluten network formation (Shafi *et al.*, 2021) [5]. Swelling power and gelatinization temperature significantly influence product texture and sensory attributes. Higher amylopectin content enables formation of stable gels upon heating, contributing to cohesive crumb structure in baked goods and crisping behaviour in fried or extruded snacks (Thakur *et al.*, 2019) [7].

Gelatinization behaviour of WCF starch typically occurs at moderate temperatures, facilitating early viscosity development during baking and reducing the risk of structural collapse in gluten-free batters lacking elasticity (Singh & Khan, 2022) [6]. Its paste clarity and low retro gradation tendency are advantageous in maintaining product softness during storage. Additionally, resistant starch in WCF contributes to delayed digestion, improving glycaemic response and supporting gut micro biota health (Priya *et al.*, 2020) [4].

Oil absorption capacity of WCF is significantly lower than that of cereal flours, which supports lower fat uptake during frying and enhances the development of healthier snack products (Heena *et al.*, 2024) [1]. Film-forming and binding properties further support its role in edible coating materials, packaging films, and structural reinforcement in composite flour systems. However, functional properties are highly dependent on processing techniques such as blanching, drying temperature, particle-size reduction, and pregelatinization, which may modify starch crystallinity and hydration behaviour (Makroo *et al.*, 2021) [5].

Processing Methods and Modification Approaches

Processing of water chestnut into flour involves multiple unit operations, each influencing final product quality and stability. Washing and thermal treatments such as blanching or boiling assist enzyme inactivation, colour retention, and microbial safety, while peeling and controlled drying ensure efficient milling into uniform particle sizes (Priya *et al.*, 2020) [4]. Drying temperature plays a critical role: high-heat drying may cause starch granule disruption and functional deterioration, whereas freeze drying preserves native structure and improves rehydration properties (Thakur *et al.*, 2019) [7].

Milling refinement is essential to minimize graininess and improve batter smoothness for bakery applications. However, extremely fine milling can increase starch damage, resulting in rapid hydration and undesirable viscosity changes (Fuertes *et al.*, 2024) [1]. Fractionation techniques such as air classification can produce enriched starch or fiber fractions targeted for specific food uses (Makroo *et al.*, 2021) [5].

Modification approaches are increasingly employed to overcome gluten deficiency in WCF. Hydrocolloids including guar gum, xanthan gum, and CMC significantly enhance dough viscoelasticity, gas retention, and crumb elasticity (Shafi *et al.*, 2021) [5]. Physical modification methods such as annealing, heat-moisture treatment, extrusion, and pregelatinization alter starch crystallinity to improve solubility, resistance to retrogradation, and expansion during snack processing (Heena *et al.*, 2024) [1].

Enzymatic modification—using amylases or debranching enzymes—offers targeted improvement in starch fractionation and film-forming capabilities while maintaining clean-label requirements. Composite flour technology is widely adopted to improve machinability and sensory acceptance by blending WCF with rice, sorghum, millets, or legume flours, while protein supplements like soy isolates provide structural reinforcement in gluten-free bread (Singh & Khan, 2022) [6].

Bakery Product Applications

Water chestnut flour has been successfully incorporated into a range of gluten-free bakery products including biscuits, cookies, muffins, and cakes. Its naturally sweet flavour and fine texture contribute to desirable organoleptic qualities, while the high dietary fiber content enhances moisture retention and prolongs freshness (Shafi *et al.*, 2021) [5]. However, WCF lacks gluten-forming proteins, resulting in limited gas-holding capacity during leavening. Therefore, blending with rice or millet flours and adding hydrocolloids such as xanthan gum improves loaf volume, softness, and crumb uniformity (Singh & Khan, 2022) [6].

In cookies and biscuits, WCF supports desirable crispness and brittleness due to its starch-based matrix, making it highly suitable for short dough products. Inclusion levels between 30-60% have shown improved sensory acceptability and enhanced mineral content compared to wheat-based products (Priya *et al.*, 2020) [4]. In cakes and muffins, WCF assists in forming a fine crumb structure, although controlled water addition and emulsifier supplementation are necessary to prevent density increase and collapse (Thakur *et al.*, 2019) [7].

Furthermore, bakery products formulated with WCF have demonstrated improved antioxidant properties and reduced glycaemic index, highlighting their relevance for therapeutic and health-promoting food markets (Heena *et al.*, 2024) [1]. Thus, WCF adds both functional and nutritional enrichment while meeting the increasing global demand for gluten-free bakery products.

Snack and Extruded Product Development

Water chestnut flour (WCF) is highly suitable for fried and extruded snack applications due to its amylopectin-rich starch structure, which enables puffing and crisp texture development under high-temperature treatment (Makroo *et al*., 2021) [5]. Low oil absorption ensures reduced fat uptake in fried snacks such as chips and wafers, making them healthier alternatives to wheat- or potato-based products (Shafi *et al*., 2021) [5].

Extrusion processing provides structural modification through starch gelatinization and molecular reorganization, improving product expansion and break strength. Blending WCF with cereals or tuber starches such as tapioca enhances expansion ratio and reduces fracture defects in puffed products. Incorporation of hydrocolloids improves cohesiveness and reduces brittleness in gluten-free noodles, enabling smoother texture and better tolerance to cooking stress (Heena *et al*., 2024) [1].

WCF is also used in snack bars and roasted products as a nutrient-dense ingredient contributing fiber, resistant starch, and mineral bioavailability—attributes attractive for sports nutrition and weight management consumers (Priya *et al*., 2020) [4]. Continued optimization of extrusion variables—temperature, screw speed, feed moisture—will further improve the commercial viability of WCF-based snacks.

Traditional and Ethnic Food Applications

Water chestnut flour is deeply integrated into traditional South Asian diets, particularly during religious fasting periods due to its gluten-free status and cultural acceptance. It is commonly processed into flatbread (chapatti/roti), sweet puddings (halwa, kheer), dumplings, and fried snacks used in Indian “upwas” foods (Thakur *et al*., 2019) [7]. Its inherent smooth texture and mild sweetness enhance consumer acceptance in sweet and savoury products.

Traditional usage supports a stable, year-round domestic demand; while modernization efforts such as dehydration stabilization, vacuum packaging, and improved milling are enhancing shelf stability and distribution reach (Shafi *et al*., 2021) [5]. Ethnic food manufacturers are increasingly incorporating WCF into ready-to-eat and ready-to-cook product lines, expanding market reach beyond regional boundaries.

As interest in culturally rooted functional foods increases internationally, WCF-based ethnic products hold significant potential for global commercialization.

Challenges, Storage Behaviour, and Industrial Prospects

Although water chestnut flour offers strong nutritional and functional advantages, several challenges limit its widespread industrial adoption. Being naturally gluten-free, WCF lacks the viscoelastic protein network required for optimal gas retention and dough machinability. This often results in compact textures, reduced loaf volume, and poor structural stability in leavened bakery products, necessitating reliance on hydrocolloids or other structural enhancers (Makroo *et al*., 2021; Singh & Khan, 2022) [5, 6]. Additionally, variability in chemical composition due to cultivar differences, geographical origin, and seasonal harvesting contributes to inconsistencies in product quality and sensory attributes, creating difficulties in large-scale standardization (Priya *et al*., 2020) [4].

Storage behaviour of WCF must be carefully managed because of its hygroscopic nature and susceptibility to oxidative deterioration. Moisture reabsorption during storage can lead to caking, microbial growth, and reduced shelf-life stability, especially in high-humidity environments (Fuertes *et al*., 2024) [1]. Furthermore, lipid oxidation and starch retro gradation negatively affect sensory properties, contributing to texture hardening, staling, and undesirable flavour development in processed foods. Advanced packaging systems such as vacuum-sealing and modified atmosphere technologies are recommended to maintain product integrity by limiting oxygen exposure and moisture migration (Thakur *et al*., 2019) [7].

Despite these constraints, the industrial prospects for WCF remain highly favourable. Rising global awareness of gluten intolerance and demand for clean-label, allergen-free foods continue to drive commercial interest. WCF aligns well with current market trends focused on health-enhancing ingredients due to its resistant starch content, low glycaemic index, and presence of essential minerals (Shafi *et al*., 2021) [5]. Technological innovations such as mechanized peeling, optimized drying, enzymatic modification, and composite flour strategies are gradually improving production efficiency and product performance, enabling broader utilization in bakery and snack sectors (Heena *et al*., 2024) [1].

Growing research investment, improved supply chain infrastructure, and expansion of value-added product lines are expected to accelerate adoption of WCF in both domestic and international food industries. With continued advancements in processing and quality standardization, water chestnut flour holds strong potential to become a competitive and sustainable gluten-free ingredient for the modern food sector.

Conclusion

Water chestnut flour offers a strong combination of nutritional quality, desirable functional characteristics, and gluten-free compatibility. Its applications span bakery, snacks, and traditional foods, supporting both cultural relevance and contemporary dietary needs. While challenges related to texture control, handling, and shelf stability remain, ongoing research and process innovation are enabling improved product quality and scalability. Strengthening supply chain infrastructure and promoting product standardization will further enhance the global market presence of water chestnut flour as a sustainable, value-added ingredient for health-oriented food systems.

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