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Exploring the therapeutic and industrial applications of a novel fruit: Water chestnut (*Trapa natans* L.)

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Abstract

Water chestnut (Trapa spp.) commonly known as singhara in India, is a floating-leaved aquatic plant with high edible and medicinal value. The kernels are refreshing, delicious to eat and highly nutritious to be used in many Ayurvedic compositions as coolant, diuretic, aphrodisiac, antidiarrhoeal, appetizer, astringent, and tonic. Its byproduct the pericarp contains phytochemical compounds with significant nutritional and functional potential. However, the pericarp has been overlooked and discarded, primarily utilized as animal feed. Water chestnut finds application across diverse sectors, both in food and non-food industries. Therefore, delving deeper into its chemistry and potential uses could unveil strategies for harnessing this aquatic plant. This review provides an overview of the chemical composition, processing methods, nutritional benefits, and the various food, therapeutic, and industrial applications of different parts of water chestnut from various species. Additionally, it explores the correlations between the various endogenous components and the potential utilization of water chestnuts.

1. Introduction

Water chestnut, a type of annual aquatic plant, belongs to the genus *Trapa* within the Trapaceae family. It is commonly encountered in freshwater environments such as wetlands, lakes, ponds, and slow-moving sections of rivers, spanning tropical, subtropical, and temperate regions (Adkar *et al.,* 2014). The plant's floating leaves typically display a rhomboid or ovate shape, ranging from 2 to 6.5 cm in diameter, with dark green coloring on the upper surface and reddish-purple underneath. Its submerged stems, which can extend up to lengths of 1 to 5 m, anchor into the mud through branched roots. Water chestnut produces starchy fruits characterized by tough rinds and distinctive spikes (Zhu, 2016).

The water chestnut (*Trapa natans* L.) is occasionally classified within the family Trapaceae. The generally reported species of water chestnut: *T. natans, T. quadrispinosa, T. incisa, T. bispinosa, T. japonica, T. manshurica, T. acornis* and *T. taiwanensis* (Chiang *et al.,* 2009; Qaiyum *et al*., 2022; Zhu, 2016). These species are differentiated based on fruit morphology, such as the number of horns present, variability in vegetative growth, yield and colour (Chiang *et al.,* 2007). The water chestnut is also known as water caltrop or water-nut.

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Water chestnut could be utilized for both culinary and medicinal purposes in India and China (Adkar *et al.,* 2014). In the Indian Ayurvedic system, water chestnut, is known as "Singhara," which holds significance both as a medicinal herb and as a food item (Zhu, 2016). Despite its historical uses, the introduction of water chestnut to North America in the 1800s led to its classification as a noxious weed, causing ecological disruptions (Riggs *et al.,* 2004). However, recent literature suggests potential applications of water chestnut in diverse areas such as food production, energy generation, and habitat restoration.

Approximately 80 per cent of the water chest is comprised of kernel, with the remaining 20 per cent constituting the peel. The kernel of water chestnut is a nutrient-rich and is encased within a hard, protective shell. The kernel boasts a crisp, white flesh with a subtly sweet taste and a crunchy texture. These kernels are rich in carbohydrates, vitamins, and minerals such as potassium and magnesium. It also serves as a valuable source of energy and essential nutrients (Hussain *et al.,* 2019). Additionally, they contain dietary fiber, which aids in digestion and promotes gastrointestinal health. Water chestnut kernels are enjoyed raw, boiled, and steamed in Indian cuisine. It is also incorporated into various dishes ranging from salads and stir-fries to desserts and snacks (Mukhlish *et al.,* 2023). Beyond its culinary appeal, the kernel of the water chestnut also holds cultural significance in many regions where it is consumed, for adding both flavor and nutritional value to traditional cuisines in different part of India. Moreover, in flood-prone regions like Bangladesh, water chestnut could also contribute towards food security efforts (Riggs *et al.,* 2004).

The peels of the water chestnut, often considered waste, presents both challenges and opportunities in its management (Pinto *et al.,* 2021). As a waste byproduct, it poses disposal issues, contributing to environmental burdens if, not managed effectively. However, innovative approaches can transform this waste into a valuable resource. Processing techniques such as composting or bioconversion can break down peel, converting it into organic matter or biofuels (Zhu, 2016). Moreover, its fibrous nature renders it suitable for applications in biodegradable packaging materials or as a component in manufacturing textiles or paper. By harnessing the potential of the water chestnut pericarp, waste can be minimized, and sustainable solutions can be developed, aligning with the principles of a circular economy and environmental stewardship.

The versatile applications of this aquatic plant and its peels could offer valuable economic opportunities in terms of food, medicine, and energy production. This review seeks to offer an understanding of the chemical composition, nutritional attributes, processing techniques, and possible uses of water chestnuts, with the goal of promoting its widespread utilization. Additionally, it underscores the nutraceutical aspect of their bioactive compounds in combating various ailments, aiming to bolster the creation of evidence-based functional food products and explore their potential industrial applications as a valuable ingredient for future endeavors.

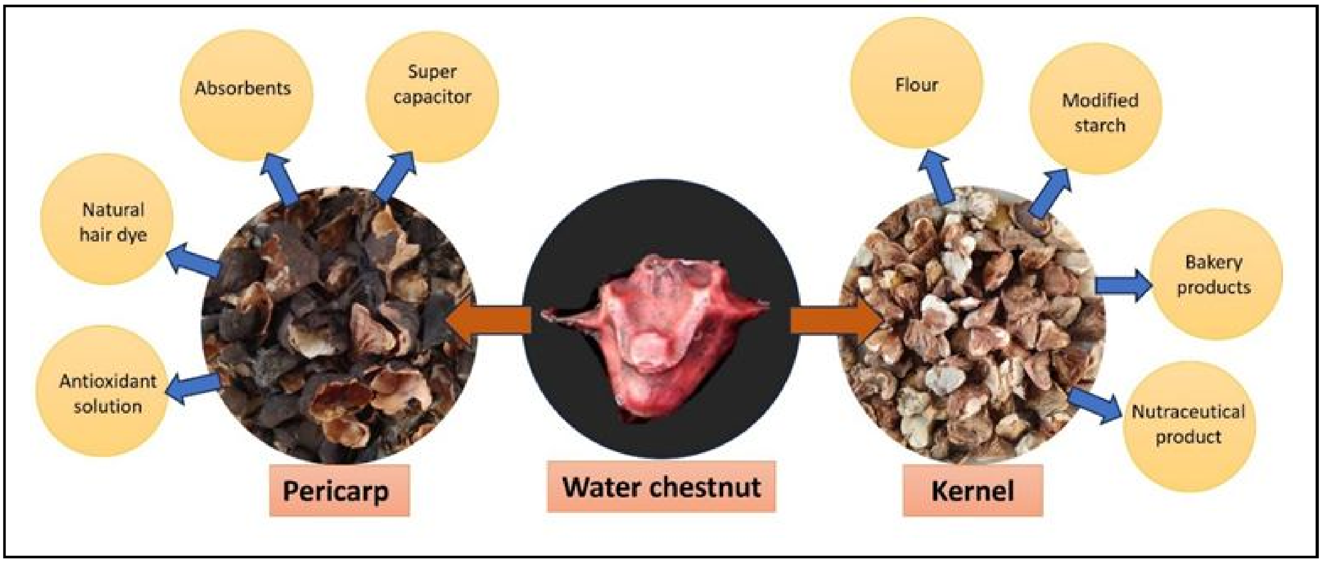

Figure 1: Food, therapeutic, and industrial value of water chestnut.

2. Chemical composition of water chestnut

The water chestnut has significant proportions of starch, dietary fibers, proteins, and minerals. Approximately, four fifths of the water chest kernel's dry weight is starch. The starch of different species of water chestnut showed diverse characteristics, including granule morphology, crystallinity, amylose content, and functional properties. During morphological study, it was found that the starch granules of water chestnuts are oval in shape that increased during growth periods. The crystallinity of granules is either A-type or C_A-type. The types of crystallinities remain the same throughout the growth periods of water chestnut. Amylopectin of water chestnuts has minimal number of DP 6-12 chains and a prominent number of DP 13-24 chains (Chiang *et al.,* 2009). The starch of high-amylose containing varieties of water chestnut exhibits strong gelling property, a high final viscosity of pasting, and high storage modulus. Unlike crystallinity type, enthalpy of gelatinization, gelatinization temperature, solubility, peak viscosity, final and setback viscosity of pasting, and swelling property of starch increased during growth period (Kang *et al.,* 2022).The dietary fiber content in water chestnut's kernels is relatively low, and it increases to 0.8 per cent during the growth. The mannoglucan isolated from water chestnut kernel showed macrophage, splenocyte, and thymocyte activation (Sarkar *et al.,* 2012). The protein contents in kernels of water chestnuts increased during growth and at maturity (42 days after flowering) reached approximately to 6-7 per cent (dry basis). Major amino acids are aspartic acid, glutamic acid, and arginine accounted for 10, 17, and 9 per cent of the protein, respectively (Chiang *et al.,*2009). Water chestnuts are considered as a good source of protein in terms of essential amino acid composition. However, research on the properties and structures of water chestnut proteins is limited. Minerals such as sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), phosphorus (P), and iron (Fe) were identified in some species of water chestnut, and their concentrations observed to rise as the plants matured. Notably, water chestnuts were noted as a notable source of potassium, with levels reaching approximately 2 g/kg on a dry basis (Chiang *et al.,* 2009).

3. Therapeutic value of water chestnut

Water chestnut exhibits a diverse array of potential health benefits, including anticancer properties, antimicrobial effects, antiatherogenic, antihyperglycemic, immunoenhancing, anti-inflammatory, hepatoprotective, antiageing, and antioxidant activities as shown in Table 1 (Zhu, 2016).

Studies have shown that it can impede the proliferation of various cancer cells, including human promyelocytic leukemia HL60 cells, HepG2 human hepatocarcinoma cells, SGC7901 human gastric cancer cells, and the human prostate cancer cell line PC-3 (Zhu, 2016). This effect is attributed to compounds present in the extracts of water chestnuts. Additionally, a lignan called cis-hinokiresinol, derived from water chestnut, has demonstrated antiatherogenic properties *in vitro*. It achieves this by inhibiting human acyl-CoA cholesterol acyltransferases enzyme, as well lipoprotein-associated phospholipase A2 and reduces the amount of low-density lipoprotein (Lin *et al.,* 2013; Song *et al.,* 2007). Sarkar *et al.,* 2012 reported that mannoglucan present in water chestnut is very effective to activate macrophages in mice during their animal study. It has potential to enhance immune system.

Extracts derived from the peels of water chestnut has antimicrobial activity especially against Gram-positive bacteria. They also demonstrate moderate inhibition against Gram-negative bacteria, with minimal impact on fungi. The minimum inhibitory concentration against Gram-positive bacteria was reported to be 0.5 mg/ml (Wang *et al.,* 2011). This antimicrobial activity is attributed to the presence of polyphenols in water chestnut, which are likely to interact with microbial components, particularly cell membranes, leading to inhibition (Zhu, 2016). Although, the specific compounds responsible for the antimicrobial activity require further investigation.

Water chestnut exhibits antihyperglycemic effects by reducing glucose levels; hepatoprotective properties against liver damage induced by toxins; anti-skin photoaging effects by protecting against UV rays induced skin damage; anti-inflammatory actions both *in vitro* and *in vivo*, and antioxidant activities attributed to its phenolic content (Kim *et al.,* 2014; Zhu, 2016).

The hepatoprotective properties of peel extracts from *T. japonica* were investigated by Kim *et al.* (2014). Their study showed that extracts have ability to prevent tertiary butylhydroperoxide induced toxicity by enhancing cell viability. Furthermore, the extract showed a reduction in production of reactive oxygen species and inhibited oxidative damage and mitochondrial dysfunction (Kim *et al.,* 2014; Zhu, 2016).

Various studies reported that water chestnut possesses antioxidant properties due to its phenolic content, which has been linked to a decreased likelihood of developing chronic diseases such as cancer, cardiovascular disease, and neurodegeneration (Zhu, 2016; Kim *et al.,* 2014; Yasuda *et al.,* 2014). The phenolic content in water chestnut varies across different parts of the plant, with peels/rind/pericarp generally containing higher levels compared to kernels. Its total antioxidant activity and free radical scavenging activity is higher than vitamin C. Apart from phenolic component, non-starch polysaccharides also contribute in antioxidant activity (Wang *et al.,* 2011).

Table 1: Therapeutic application of water chestnut

Parts of water chestnut	Species	Compound/extract	Therapeutic effect	References
Pericarp	*T. taiwanensis*	Hydrolysable tannins, tellimagrandin II(TGII, 1) and 1,2,3,4,6-pentagalloyl glucopyranose (PGG, 2)	Radical scavenging	Wang *et al.,* 2019
	T. japonica	Aqueous extract	Radical scavenging, anti-inflammatory	Kim *et al.,* 2014
	T. acornis *T. bispinosa* *T. quadrispinosa*	Methanol and aqueous extracts	Radical scavenging, reducing power, antimicrobial, antiproliferative	Yu and Shen, 2015
	T. japonica	Polyphenols	Radical scavenging, postprandial hyperglycemia	Yasuda *et al.,* 2014
	T. japonica	Aqueous and ethanol extracts	Radical scavenging, reducing power, antioxidative damage in Chang cells	Kim *et al.,* 2014
	T. acornis, *T. bispinosa,* *T. quadrispinosa*	Methanol and aqueous extracts	Radical scavenging, reducing power, inhibition on growth of human gastric cancer cells	Lin *et al.,* 2013
	T. taiwanensis	Hot water extract	Radical scavenging, reducing power, hepatoprotection	Wang *et al.,* 2011
	T. natans	Aqueous extract	Radical scavenging	Malviya *et al.,* 2010
	T. japonica	Methanol extract	Radical scavenging, postprandial glycemiccontrol	Kang *et al.,* 202
	T. taiwanensis	Methanol extract	Radical scavenging,cupric ion chelating	Chiang *et al.,* 2009
Kernels	*T. japonica*	Powder		Kang *et al.,* 2022
	T. bispinosa	Mannoglucan	Radical scavenging, immuno-enhancing	Sarkar *et al.,* 2012
	T. pseudoincisa	Cis-hinokiresinol	Antiatherogenic	Song *et al.,* 2007
	T. pseudoincisa	Cis-hinokiresinol	Radical scavenging	Song *et al.,* 2007

4. Processing of water chestnut as food product

Water chestnuts is highly perishable and is not an all-season fruit. Immature water chestnut kernel is often preferred for consumption. To prolong its shelf-life, freshly cut fruit was coated with various concentration of chitosan solutions then stored at 4°C with a relative humidity of 80-85 per cent for 15 days (Zhan *et al.,* 2011). Application of chitosan coating (at 1% and 2% concentrations) effectively reduced the browning and weight loss, along with maintaining the levels of total phenolics, ascorbic acid, soluble solids, and titratable acidity. Notably, the activities of phenylalanine ammonia-lyase, polyphenol oxidase, and peroxidase remained unaffected. Further exploration into extending the shelf-life of freshwater chestnut products through additional packaging methods like atmosphere control need to be done.

The shelf-life and storage capabilities can be enhanced with the use of processing techniques such as drying (Singh *et al.,* 2011; Zhu, 2016) and coating. Converting the fruits into dried powders can extend their shelf-life. Before drying of water chestnut kernels, they are sliced and then immersed in citric acid, potassium metabisulfite, and sodium hydroxide solutions for 30 min to achieve desirable color. Thereafter, it is dried and ground in flour of average particle size of 268 ¼ m. The flour offers a viable solution to minimize losses and broaden its applications (Singh *et al.,* 2011; Zhu, 2016).

The deterioration in quality of freshwater chestnut can be attributed to enzymatic browning caused due to heating. During heating the endogenous enzymes such as polyphenol oxidase and peroxidase of water chestnut react with phenolic components and turn them into brown colour. So, careful selection of temperature, heating duration, and pH is crucial to prevent color loss due to enzymatic browning during processing (Ciou*et al.,* 2011).

Starch is primary constituent of water chestnut fruit, presents a promising novel resource for various applications (Zhu, 2016). Researchers have reported that heat moisture treatment, annealing, acid hydrolysis, and dry heating with or without ionic gums enhanced the functional properties of water chestnut starch. The heat moisture decreases the solubility and swelling power, increases gelatinization temperatures and alters pasting viscosity of starch. Acid hydrolysis, on the other hand, reduces pasting viscosity, water and oil binding capacity, swelling capacity, and amylose content with improving light transmittance and water solubility of water chestnut starch. The starch derived from water chest underwent modification through acid hydrolysis and heat-moisture treatment to produce biodegradable films, with glycerol serving as the plasticizer. These films exhibited varying properties depending on the treatment method such as native starch displayed good pliability, while enhanced tensile strength to films made from treated starches (acid and heat-moisture treatment). This modified form of water chestnut starch can be used as thickener, fat replacer, and porous matrix for drug delivery.

Moreover, water chestnut flour can be successfully incorporated into various food products, such as cookies and noodles. Water absorption of composite flour could be increased by adding water chestnut flour, resulting in cookies with improved fracture strength but reduced dimensions (Choudhury and Chaudhary, 2023). Similarly, in noodle production, blending water chestnut flour with wheat flour shortened cooking time, altered texture attributes, and maintained overall acceptability comparable to traditional wheat noodles. These findings suggest the potential of water chestnut flour as a functional ingredient in novel food product development, particularly for gluten-free applications catering to individuals with celiac disease (Hussain *et al.,* 2019; Mir *et al.,* 2015). Some developed food products by incorporating water chestnut flour are shown in Table 2.

Table 2: Application of water chestnut as food products

Species	Product	Formulation	References
T. bispisona	Noodles	Noodles preparation involves a blend of 60% water chestnut, 20% potato, and 20% sweet potato, supplemented with 10% skimmed milk powder.	Ahsan *et al.,* 2023
T. natans	Nankhatai and biscuit	The nankhatai and biscuit recipe is based on the weights of wheat flour, water chestnut flour, ghee, sugar, desiccated coconut, curd, ammonium bicarbonate, and sodium bicarbonate.	Punia and Sindhu, 2021
T. bispinosa	Pudding	For making pudding, buffalo milk with 6% fat and 9% SNF was used, along with the addition of 20% water chestnut powder and 20% honey.	Mukhlish *et al.,* 2023
T. natans	Cookies	Blends of water chestnut flour (WCF), with refined wheat flour (WF) was done for cookies.	Shafi *et al.,* 2016
T. natans	Cookies	Cookie dough was made using varying proportions of wheat flour, water chestnut flour, and cassava flour.	Bala *et al.,* 2015

5. Processing of water chestnut peel for industrial use

The water chestnut peel accounts for approximately 20 per cent of the total fruit weight. The peels having high starch and lignocellulose content is anticipated to be an efficient biomass source for producing ingredients for industrial use. Certainly, water chestnuts have been utilized in producing L-lactic acid and glucose through separate fermentation and saccharification processes (Zhu, 2016).

Traditionally, this byproduct has been burned as fuel in factories, but new strategies are being explored for its assessment and reuse. These include its potential use as heavy metal absorbents, raw materials for bioethanol and lignin production, wood adhesives, and pigment sources for dyeing (Table 3). Moreover, there is growing interest in utilizing water chestnut waste as a source of bioactive compounds having various health benefits (Kim *et al.,* 2014; Yasuda *et al.,* 2014).

Water chestnut peels were ground into powder to create absorbents for cleaning industrial wastewater. Activated carbon (Fe-modified) was derived from water chestnut pericarp powder is a promising absorbent for mutagenic Cr (VI) and carcinogenic from industrial wastewater (Liu *et al*., 2010); efficient removal of rhodamine B dye from textile wastewater (Khan *et al.*, 2013); removal of reactive orange 122 dye from dye effluent (Saeed *et al*., 2015) and generating carbon dots (Mewada*et al.,* 2013).

Water chestnuts' peels are converted into biochar with activating agents (KOH) and inorganic nanoparticles (ZnO or $CaCO_3$) to create the mesopores and micropores into the Water chestnuts biochar after high-temperature pyrolysis that can make it super capacitor (Ma *et al.,* 2022).

Table 3: Industrial application of water chestnut

Part	Product	Application	References
Water chestnut's pericarp	N/S-doped porous carbons	N/S-doped porous carbons were synthesized for supercapacitor	Ma *et al.,* 2022
Water chestnut's pericarp and eggshell	Nitrogen-doped multiporous carbons	Preparation of nitrogen-doped multiporous carbons (N-mpcs) as eco-friendly materials for catalyzing oxygen reduction reactions.	Hsu *et al.,* 2021
Water chestnut's pericarp	N-doped porous carbonaceous sorbents	N-doped porous carbonaceous sorbents for CO_2 capture	Zhao *et al.,* 2021
Water chestnut's pericarp	Mesoporous activated carbon (AC)	Potent adsorbent for eliminating cationic substances from water solutions.	Tsai and Jiang, 2023
Water chestnut's pericarp	Mesoporous activated carbon (AC)	Removal of methylene blue	Lin and Tsai, 2021
Water chestnut's pericarp	Acid-activated absorbent	Removing hexavalent chromium	Kumar *et al.,* 2020
Water chestnut's pericarp	Biosorbent	Removing Cr (VI) ions from aqueous solutions	Kumar *et al.,* 2019
Water chestnut's pericarp	Biochar	Absorbed emulsions	Wang *et al.,* 2022
Water chestnut's pericarp and gelatin/alginate	Biochar	Cadmium removal from contaminated water	Zong *et al.,* 2023
Water chestnut's pericarp	Hair dye	Ecofriendly and natural hair dye extraction	Liu *et al.,* 2023
Water chestnut's pericarp	Iron-doped and porous biochar	Treatment of urea from swimming pool water	Li *et al.,* 2022
Water chestnut's pericarp	Carbon catalysts	Cooperative adsorption and heterogeneous activation of peroxymonosulfate for tetracycline oxidation *via* electron transfer and non-radical pathway	Yang *et al.,* 2022
Water chestnut's shell	Fe–Ce/biochar composites	Degradation of phthalate esters in marine sediments	Dong *et al.,* 2020
Water chestnut shell and wood	Biochars	Adsorption of Cr (III) and Cu (II) in solutions	Zhang *et al.,* 2019
Water chestnut shell	Sodium ion battery anode	High sodium storage capacity and high performance as anode	Wang *et al.,* 2019
Water chestnut shell and wood	Adsorbents	Ni (II) removal from aqueous solution	Mukhlish *et al.,* 2023

6. Conclusion

Water chestnut's kernel and peel represent a promising reservoir of functional compounds that can be utilized to enhance, fortify, and innovate food products. The chemical analysis of kernel and peel indicates their rich nutritional profile, containing essential nutrients with potential health benefits. It possesses varied dietary and therapeutic benefits such as hepatoprotection, anticancer, antioxidant effects, and antihyperglycemic. Water chestnut can be employed in treating wastewater and producing glucose and L-lactic acid. The modification water chestnuts' starch can lead to create biodegradable films, while the flour derived from it can be utilized in the formulation of various food products. It could be the beneficial source for regions grappling with nutritional deficiencies, further research is recommended to fully exploit their nutritional and functional properties.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article..

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