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Phytochemical Properties and Nutritional Benefits of Lotus Rhizome (*Nelumbo nucifera*): A Comprehensive Review

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Abstract The lotus rhizome (*Nelumbo nucifera*), a significant component in traditional medicine and cuisine across Asia, has gained attention for its diverse phytochemical properties and nutritional benefits. This study systematically examines the existing literature on the phytochemical composition, bioactive compounds, and nutritional value of lotus rhizome. Key phytochemicals, including polyphenols, flavonoids, and alkaloids, are explored for their antioxidant, anti-inflammatory, and anti-carcinogenic properties. Nutritional analysis reveals the rhizome's rich content of essential vitamins, minerals, and dietary fiber, emphasizing its role in promoting health and preventing chronic diseases. This study also discusses the potential applications of lotus rhizome in functional foods and nutraceuticals, highlighting its therapeutic potential. Future research directions are suggested to further elucidate the mechanisms underlying the health benefits of lotus rhizome and to optimize its use in food and pharmaceutical industries.
Keywords Lotus rhizome (*Nelumbo nucifera*); Phytochemicals; Bioactive compounds; Antioxidant properties; Traditional medicine

1 Introduction

The lotus rhizome (*Nelumbo nucifera*), also known as the sacred lotus, Indian lotus, or Chinese water lily, is an aquatic perennial plant that has been extensively cultivated and utilized in various parts of Asia for over 2000 years (Sharma et al., 2017). Traditionally, different parts of the lotus plant, including the rhizome, seeds, leaves, and flowers, have been used as both food and medicine (Fatima et al., 2018). The rhizome, in particular, is a significant edible part of the plant and is known for its unique texture and flavor, making it a popular ingredient in many Asian cuisines (Thanushree et al., 2017; Yamini et al., 2019). Additionally, the lotus rhizome is often used in traditional medicine systems such as *Ayurveda* and traditional Chinese medicine due to its numerous health benefits.

The phytochemical properties of the lotus rhizome are of great interest due to the presence of various bioactive compounds that contribute to its medicinal and nutritional value. These compounds include alkaloids, flavonoids, glycosides, terpenoids, steroids, and polyphenols, which are known for their diverse pharmacological activities (Sharma et al., 2017; Yamini et al., 2019). Research has shown that these phytochemicals exhibit antioxidant, anti-inflammatory, immune-modulatory, antiviral, hepatoprotective, cardioprotective, and hypoglycemic activities, among others (Bishayee et al., 2022; Zhu et al., 2022). Understanding the phytochemical composition of the lotus rhizome is crucial for exploring its potential applications in food, pharmaceuticals, and nutraceuticals.

The nutritional benefits of the lotus rhizome are equally noteworthy. It is a rich source of carbohydrates, proteins, and dietary fiber, making it a valuable addition to the diet (Yamini et al., 2019). The rhizome also contains essential vitamins and minerals, contributing to its overall nutritional profile (Sharma et al., 2017). Studies have highlighted the potential of lotus rhizome extracts in enhancing the nutritional value of food products, such as bread sticks, by increasing their phenolic and flavonoid content and improving their antioxidant capacity (Thanushree et al., 2017). Moreover, the consumption of lotus rhizome has been associated with various health benefits, including the management of cardiovascular diseases, obesity, diabetes, and inflammation (Fatima et al., 2018; Bishayee et al., 2022).

The primary objective of this study is to provide a comprehensive overview of the phytochemical properties and nutritional benefits of the lotus rhizome. By synthesizing existing research, this study highlights the potential health benefits and therapeutic applications of the rhizome. Future research directions will also be discussed, focusing on the need for more in-depth studies on the bioavailability, pharmacokinetics, and possible toxicity of lotus rhizome-derived phytochemicals. This study will serve as a valuable resource for researchers, healthcare professionals, and the food and pharmaceutical industries, promoting the further exploration and utilization of this remarkable plant.

2 Phytochemical Composition of Lotus Rhizome

2.1 Overview of phytochemicals

The lotus rhizome is a rich source of various phytochemicals, which contribute to its nutritional and medicinal properties. These phytochemicals include alkaloids, flavonoids, tannins, polyphenols, and other bioactive compounds. The presence of these compounds has been linked to numerous health benefits, such as antioxidant, anti-inflammatory, and anticancer activities (Wang et al., 2021a; Bishayee et al., 2022).

2.2 Alkaloids

Alkaloids are one of the primary bioactive compounds found in the lotus rhizome. They are known for their pharmacological effects, including anti-obesity, anti-diabetic, and neuroprotective activities. The main alkaloids identified in lotus rhizome include *aporphines*, *1-benzylisoquinolines*, and *bisbenzylisoquinolines*. These compounds have shown potential in treating various health conditions, although their bioavailability is relatively low and can be enhanced through technological modifications (Wang et al., 2021b; Tungmunnithum et al., 2022).

2.3 Flavonoids

Flavonoids are another significant group of phytochemicals present in the lotus rhizome. These compounds are known for their antioxidant properties, which help in scavenging free radicals and protecting cells from oxidative stress. The main flavonoids identified in lotus rhizome include *catechin*, *kaempferol*, *quercetin*, and *hyperoside* (Figure 1). These flavonoids have been linked to various health benefits, including anti-inflammatory, anti-cancer, and anti-aging effects (Yamini et al., 2019a; Yamini et al., 2019b).

The research of Tungmunnithum et al. (2022) systematically categorizes these compounds based on their specific substituents (R1 to R5 and R6 to R8) attached to the flavonoid backbone, represented in two structural diagrams. Each flavonoid's unique glycoside and aglycone combinations provide insights into their distinct biochemical properties and potential health benefits. Understanding these structures aids in the study of their roles in medicinal applications, such as their antioxidant, anti-inflammatory, and other therapeutic properties, derived from the lotus plant.

2.4 Tannins

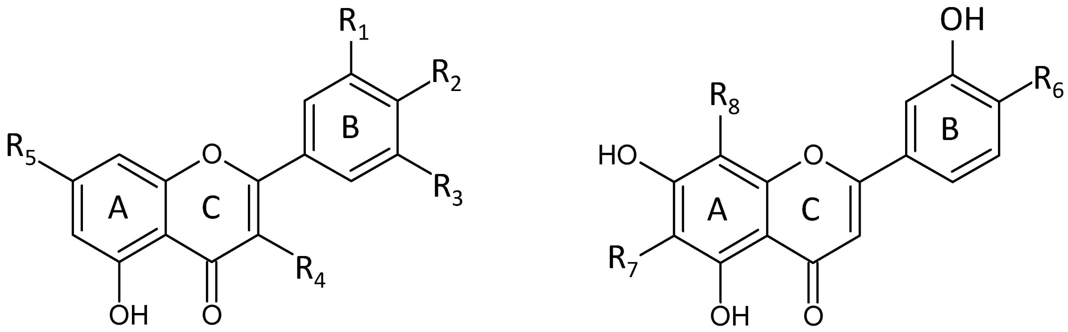
Tannins are polyphenolic compounds that contribute to the astringent taste of the lotus rhizome. They have been shown to possess antioxidant and anti-inflammatory properties. The lotus rhizome knot, in particular, has been found to have a high total tannin content, which contributes to its strong antioxidant activity. Tannins also play a role in the rhizome's potential use in food preservation and as a natural remedy for various ailments (Yamini et al., 2019a; Zhu et al., 2022).

2.5 Polyphenols

Polyphenols are a diverse group of phytochemicals that include phenolic acids, flavonoids, lignans, and stilbenes. The lotus rhizome is rich in polyphenols, which contribute to its antioxidant and anti-cancer properties. A comprehensive profiling of the lotus rhizome has identified numerous polyphenolic compounds, highlighting its potential as a source of natural antioxidants and therapeutic agents (Shen et al., 2019; Zhu et al., 2022).

2.6 Other bioactive compounds

In addition to alkaloids, flavonoids, tannins, and polyphenols, the lotus rhizome contains other bioactive compounds such as terpenoids, steroids, and glycosides. These compounds contribute to the rhizome's pharmacological activities, including hepatoprotective, cardioprotective, and hypoglycemic effects. The diverse phytochemical composition of the lotus rhizome underscores its potential for use in traditional medicine and modern therapeutic applications (Tungmunnithum et al., 2018; Chen et al., 2019; Wang et al., 2021b).



	Name	R_1	R_2	R_3	R_4	R_5
O1	Myr-3-Gal	OH	OH	OH	*O*-Gal	OH
O2	Myr-3-Glc	OH	OH	OH	*O*-Glc	OH
O3	Quer-3-Ara-Gal	OH	OH	H	*O*-Ara-Gal	OH
O4	Myr-3-Gln	OH	OH	OH	*O*-Gln	OH
O5	Rutin [1]	OH	OH	H	*O*-Rha-Glc	OH
O6	Hyperoside [2]	OH	OH	H	*O*-Gal	OH
O7	Isoquercitrin [3]	OH	OH	H	*O*-Glc	OH
O8	Kae-3-Rob	H	OH	H	*O*-Rob	OH
O9	Quer-3-Gln	OH	OH	H	*O*-Gln	OH
O10	Kae-3-Gal	H	OH	H	*O*-Gal	OH
O11	Iso-3-Rut	OCH_3	OH	H	*O*-Rut	OH
O12	Astragalin [4]	H	OH	H	*O*-Glc	OH
O13	Syr-3-Glc	OCH_3	OH	OCH_3	*O*-Glc	OH
O14	Iso-3-Glc	OCH_3	OH	H	*O*-Glc	OH
O15	Kae-3-Gln	H	OH	H	*O*-Gln	OH
O16	Kae-7-Glu	H	OH	H	OH	*O*-Glc
O17	Dio-7-Hex	OH	OCH_3	H	H	*O*-Hex
O18	Iso-3-Gln	OCH_3	OH	H	*O*-Gln	OH
19	Quer	OH	OH	H	OH	OH
20	Dio	OH	OCH_3	H	H	OH

	Name	R_6	R_7	R_8
C1	Orientin[5]	OH	H	*C*-Glc
C2	Isoorientin[6]	OH	*C*-Glc	H
C3	Vitexin[7]	H	H	*C*-Glc
C4	Isovitexin[8]	H	*C*-Glc	H
C5	Api-6-*C*-Glc-8-*C*-Glc	H	*C*-Glc	*C*-Glc
C6	Lut-6-*C*-Glc-8-*C*-Pen	OH	*C*-Glc	*C*-Pen
C7	Lut-6-*C*-Pen-8-*C*-Glc	OH	*C*-Pen	*C*-Glc
C8	Api-6-*C*-Glc-8-*C*-Xyl	H	*C*-Glc	*C*-Xyl
C9	Api-6-*C*-Xyl-8-*C*-Glc	H	*C*-Xyl	*C*-Glc
C10	Api-6-*C*-Glc-8-*C*-Ara	H	*C*-Glc	*C*-Ara
C11	Api-6-*C*-Ara-8-*C*-Glc	H	*C*-Ara	*C*-Glc
C12	Api-6-*C*-Glc-8-*C*-Rha	H	*C*-Glc	*C*-Rha
C13	Api-6-*C*-Rha-8-*C*-Glc	H	*C*-Rha	*C*-Glc

Figure 1 The chemical structures and names of the mains flavonoid *O*- (starting by O), *C-glycosides* (starting by C) and *quercetin* (Quer) and Diosmetin (Dio) aglycones from *Nelumbo nucifera* tissues (Adopted from Tungmunnithum et al., 2022)

Image caption: Flavonoid abbreviations used: Myr, *myrycetin*; Quer, *quercetin*; Kae, *kaempferol*; Iso, *isorhamnetin*; Syr, *syringetin*; Dio, *diosmetin*; Api, *apigenin*; Lut, *luteolin*. Sugar abbreviations used: Glc, *glucoside*; Gal, *galactoside*; Ara, *arabionoside*; Gln, *glucuronide*; Rut, *rutinoside*; Hex, *hexoside*; Xyl, *xylose*; Rha, *rhamnose*; Pen, *pentose*. rutin, *quercetin 3-O-rhamnopyranosyl*-(1→6)-glucopyranoside; *hyperoside*, *quercetin 3-O-galactoside*; isoquercitrin, *quercetin* 3-*O*-glucoside; Astragalin, *kaempferol* 3-*O*-glucoside; orientin, *luteolin 8-C-β-D-glucopyranoside*; isoorientin, *luteolin 6-C-β-D-glucopyranoside*; vitexin, *apigenin 8-C-β-D-glucopyranoside*; isovitexin, *apigenin 6-C-β-D-glucopyranoside* (Adopted from Tungmunnithum et al., 2022)

3 Nutritional Profile of Lotus Rhizome

3.1 Macronutrient content

Lotus rhizome is a rich source of essential macronutrients, including carbohydrates, proteins, and lipids. The primary metabolites present in the rhizome contribute significantly to its nutritional value. Carbohydrates are the most abundant macronutrient, making the rhizome a good energy source. Proteins are also present in substantial amounts, which are crucial for body repair and growth. Lipids, although present in smaller quantities, contribute to the overall nutritional profile of the rhizome (Yamini et al., 2019a).

3.2 Micronutrient content

In addition to macronutrients, lotus rhizome contains various micronutrients that are vital for maintaining health. These include vitamins and minerals that play essential roles in numerous physiological processes. The rhizome is particularly noted for its content of phenolic compounds, flavonoids, tannins, alkaloids, and other secondary metabolites, which not only contribute to its nutritional value but also provide medicinal benefits (Fatima et al., 2018; Zhu et al., 2022). These compounds have been linked to antioxidant, anti-inflammatory, and other health-promoting properties.

3.3 Dietary fiber

Dietary fiber is another important component of the lotus rhizome. It aids in digestion and helps maintain a healthy gut. The presence of dietary fiber in the rhizome makes it beneficial for digestive health and can help in managing conditions such as constipation and other gastrointestinal disorders (Yamini et al., 2019a). The fiber content also contributes to the feeling of fullness, which can aid in weight management.

3.4 Caloric value

The caloric value of lotus rhizome is primarily derived from its carbohydrate content. This makes it an excellent source of energy, especially in diets where high energy intake is required. The balance of macronutrients ensures that the rhizome provides a steady release of energy, making it suitable for inclusion in various dietary plans (Yamini et al., 2019a). In summary, the lotus rhizome is a nutritionally rich food source, offering a balanced profile of macronutrients, essential micronutrients, dietary fiber, and a significant caloric value. Its inclusion in the diet can provide numerous health benefits, supported by its rich phytochemical composition (Fatima et al., 2018; Zhu et al., 2022).

4 Health Benefits of Lotus Rhizome

4.1 Antioxidant properties

Lotus rhizome is rich in phenolic compounds, which contribute significantly to its antioxidant properties. Studies have shown that different parts of the lotus, including the rhizome, contain high levels of phenolic acids, flavonoids, and other polyphenols, which are known for their ability to scavenge free radicals and reduce oxidative stress (Zhu et al., 2022; Temviriyanukul et al., 2020) (Figure 2). The antioxidant potential of lotus rhizome has been demonstrated through various assays, such as DPPH and ABTS scavenging activities, highlighting its capacity to protect cells from oxidative damage (Zhu et al., 2022).

4.2 Anti-inflammatory effects

The anti-inflammatory properties of lotus rhizome are attributed to its bioactive compounds, which can modulate inflammatory pathways. Research indicates that lotus seed protein isolate can significantly reduce the production of pro-inflammatory mediators such as nitric oxide (NO), tumor necrosis factor-alpha (TNF-α), and interleukins (IL-6 and IL-1β) in LPS-stimulated macrophages by inhibiting the NF-κB and MAPK signaling pathways (Moon et al., 2019). This suggests that lotus rhizome may be effective in managing inflammatory conditions and reducing the risk of chronic inflammatory diseases.

4.3 Cardiovascular health

Lotus rhizome has been traditionally used to manage cardiovascular diseases, and modern research supports its cardioprotective effects. The bioactive compounds in lotus rhizome, including flavonoids and alkaloids, have been shown to improve lipid profiles, reduce hypertension, and enhance overall cardiovascular health (Chen et al., 2019; Bishayee et al., 2022). These compounds help in lowering LDL cholesterol levels and improving blood circulation, thereby reducing the risk of atherosclerosis and other cardiovascular disorders.

4.4 Antimicrobial activity

The antimicrobial properties of lotus rhizome are well-documented, with studies showing its effectiveness against a range of bacterial and fungal pathogens. The phenolic compounds and other bioactive constituents in lotus rhizome exhibit strong antimicrobial activity, which can be beneficial in preventing and treating infections (Chen et al., 2019; Bishayee et al., 2022). This makes lotus rhizome a valuable natural alternative for antimicrobial agents in both food preservation and medicinal applications.

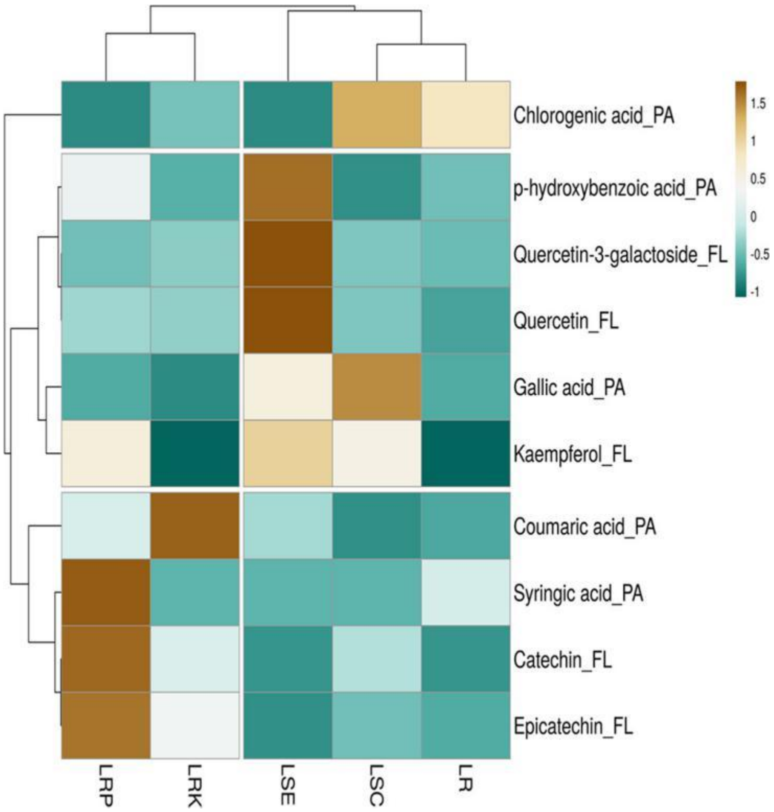


Figure 2 Heat map showing the distribution and concentration of phenolic compounds in five parts of lotus (Adopted from Zhu et al., 2022)

Image caption: Brown boxes show that constructions are higher among five samples. Blue boxes indicate lower concentrations. FL: flavonoids and PA: phenolic acids. Fruit peel samples are mentioned in abbreviations. LR: *lotus rhizome pulp*; LRP, lotus rhizome peel; LRK, lotus rhizome knot; LSC, lotus seed cotyledon; and LSE, *lotus seed embryo* (Adopted from Zhu et al., 2022)

The heat map adopted from Zhu et al. (2022) is divided into clusters that highlight the variation in phenolic content across different lotus parts: rhizome pulp (LR), rhizome peel (LRP), rhizome knot (LRK), seed cotyledon (LSC), and seed embryo (LSE). Notably, compounds like chlorogenic acid, p-hydroxybenzoic acid, and gallic acid are more prevalent in certain parts, as evidenced by the darker brown shades, while others like *catechin* and epi*catechin* show varied distributions. This visualization provides a comprehensive overview of how phenolic compounds are distributed within the lotus plant, which can be crucial for understanding its nutritional and medicinal properties.

4.5 Other health benefits

In addition to the aforementioned benefits, lotus rhizome offers a variety of other health-promoting effects. It has been found to possess anti-obesity properties, as evidenced by its ability to inhibit adipogenesis and reduce lipid accumulation in preadipocytes and animal models (He et al., 2022) (Figure 3). Furthermore, lotus rhizome exhibits neuroprotective effects, potentially aiding in the prevention of neurodegenerative diseases such as Alzheimer's (Temviriyanukul et al., 2020). Its hepatoprotective and hypoglycemic activities also contribute to its overall health benefits, making it a versatile functional food and medicinal herb (Chen et al., 2019).

The research of He et al. (2022) shows mice on the high-fat diet showed increased body weight, serum and liver cholesterol, triglycerides, LDL cholesterol, epididymal fat mass, fasting blood glucose, and insulin resistance. Conversely, the treatment group receiving FLLS-WEHI01 exhibited reductions in these parameters, indicating the compound's efficacy in mitigating the negative effects of a high-fat diet. Mechanistically, the diagram illustrates that FLLS-WEHI01 decreases the expression of C/EBPα and PPARγ, which are critical regulators of adipogenesis. This reduction leads to decreased adipogenesis gene expression (ACC, FAS), ultimately resulting in lower fat accumulation, reduced inflammation, and improved insulin sensitivity. This highlights the potential of FLLS-WEHI01 as an anti-obesity agent.

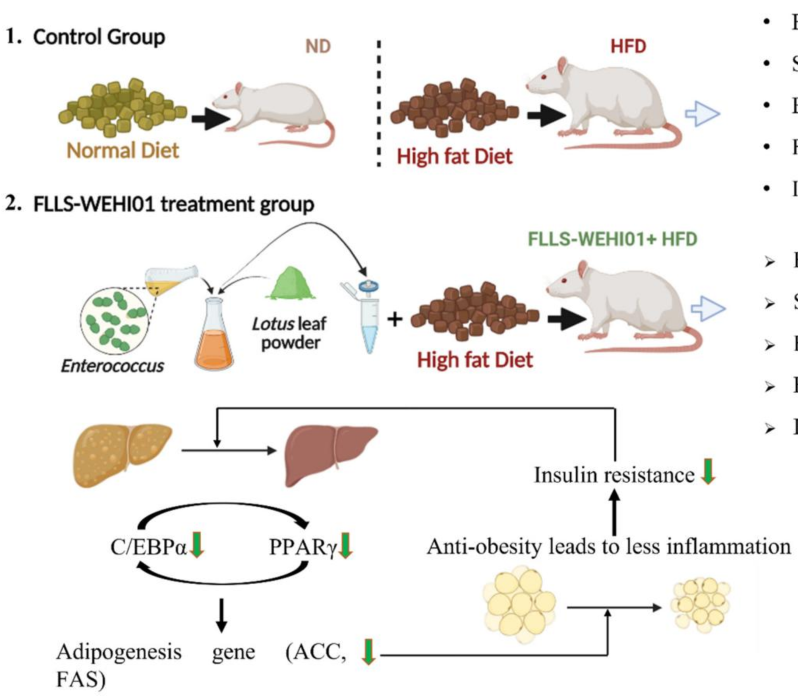


Figure 3 The schematic diagram of the anti-obesity ability of WEHI01-fermented lotus leaf supernatant (Adopted from He et al., 2022)

Image caption: ND, normal diet; HFD, high-fat diet; FLLS-WEHI01, *Enterococcus hirae* WEHI01-fermented lotus leaf supernatant; TC, total cholesterol; TG, total triglyceride; LDL-C, low-density lipoprotein cholesterol; C/EBPα, CCAAT/enhancer-binding protein α; PPARγ, peroxisome proliferator activated receptors γ; ACC, *acetyl-CoA carboxylase*; FAS, fatty acid synthase (Adopted from He et al., 2022)

5 Phytochemical Extraction and Analysis

5.1 Extraction methods

The extraction of phytochemicals from *Nelumbo nucifera*, commonly known as lotus, involves various solvents and techniques to maximize yield and efficacy. Ethanol, ethyl acetate, hexane, chloroform, acetone, and aqueous solutions are frequently used solvents for extracting bioactive compounds from different parts of the lotus, including rhizomes, seeds, and flowers (Mehta et al., 2020). The choice of solvent significantly impacts the type and quantity of phytochemicals extracted. For instance, ethanolic extracts have been shown to contain higher concentrations of phenols, flavonoids, and tannins compared to other solvents (Yamini et al., 2019a; Yamini et al., 2019b). Additionally, methanol has been used effectively to extract high contents of flavonoids and phenols from the rhizome (Ullah et al., 2018).

5.2 Analytical techniques

Various analytical techniques are employed to identify and quantify the phytochemicals present in *Nelumbo nucifera*. High-performance liquid chromatography (HPLC) coupled with photodiode array detection is a validated method for separating and quantifying flavonoids and other phenolic compounds (Tungmunnithum et al., 2022). Liquid chromatography coupled with electrospray ionization quadrupole time-of-flight mass spectrometry (LC-ESI-QTOF-MS/MS) is another advanced technique used to profile phenolic compounds in different parts of the lotus, identifying a total of 86 phenolic compounds, including phenolic acids, flavonoids, lignans, stilbenes, and other polyphenols (Zhu et al., 2022). These techniques provide comprehensive profiles of the phytochemicals, aiding in the understanding of their potential health benefits and applications.

5.3 Quantification and identification

Quantification and identification of phytochemicals in *Nelumbo nucifera* are crucial for evaluating its nutritional and medicinal properties. The total phenolic content, flavonoid content, and antioxidant activities are commonly measured using various assays. For example, the total phenolic content in lotus seed embryos was found to be 10.77±0.66 mg GAE/gf.w., while the total flavonoid content was 1.61±0.03 mg QE/gf.w. (Zhu et al., 2022). The antioxidant potential is assessed using assays such as DPPH scavenging activity, ABTS scavenging activity, and ferric ion reducing antioxidant power (FRAP) (Zhu et al., 2022). These quantifications reveal that different parts of the lotus, such as the rhizome and seed embryos, are rich sources of bioactive compounds with significant antioxidant properties.

In summary, the extraction, analytical techniques, and quantification methods employed in the study of *Nelumbo nucifera* provide a detailed understanding of its phytochemical composition. These methods highlight the plant's potential as a source of nutritionally and pharmacologically valuable compounds (Chen et al., 2019; Bishayee et al., 2022).

6 Traditional and Modern Uses of Lotus Rhizome

6.1 Traditional medicinal uses

The lotus rhizome has been utilized in traditional medicine for over 2000 years, particularly in Asian countries. It has been employed to treat a variety of ailments, including chronic dyspepsia, hematuria, insomnia, nervous disorders, cardiovascular diseases, and hyperlipidemia. The rhizome is rich in bioactive compounds such as alkaloids, polyphenols, terpenoids, steroids, and glycosides, which contribute to its medicinal properties (Chen et al., 2019; Bishayee et al., 2022). These compounds exhibit a range of pharmacological activities, including antioxidant, anti-inflammatory, immune-modulatory, antiviral, hepatoprotective, cardioprotective, and hypoglycemic effects (Yamini et al., 2019a).

6.2 Culinary applications

In addition to its medicinal uses, the lotus rhizome is also valued as a culinary ingredient. It is commonly consumed in various forms, such as fresh, dried, or pickled, and is used in a variety of dishes across Asian cuisines (Chen et al., 2019; Zhu et al., 2022). The rhizome is known for its crunchy texture and slightly sweet flavor, making it a popular addition to soups, stir-fries, and salads. Its nutritional profile, which includes carbohydrates, proteins, and essential vitamins and minerals, further enhances its appeal as a functional food (Yamini et al., 2019a; Zhu et al., 2022). The presence of phenolic compounds and flavonoids in the rhizome also contributes to its antioxidant properties, making it a health-promoting ingredient in the diet.

6.3 Modern therapeutic uses

Recent research has expanded the understanding of the therapeutic potential of lotus rhizome in modern medicine. Studies have demonstrated its efficacy in cancer prevention and intervention, highlighting its ability to combat various types of cancer through mechanisms such as apoptosis induction, cell cycle arrest, and inhibition of metastasis (Bishayee et al., 2022). Additionally, the rhizome has shown promise in managing diabetes, with in vitro studies indicating its potential to inhibit *α-glucosidase* activity and reduce blood glucose levels (Pokhrel et al., 2022). The antioxidant properties of the rhizome, attributed to its high phenolic and flavonoid content, further support its use in preventing oxidative stress-related diseases (Zhu et al., 2022). Moreover, the rhizome's anti-inflammatory and hepatoprotective effects make it a valuable candidate for developing new therapeutic agents (Chen et al., 2019). In summary, the lotus rhizome holds significant value in both traditional and modern contexts. Its diverse applications in medicine and cuisine, supported by a rich phytochemical profile, underscore its importance as a multifunctional plant with substantial health benefits.

7 Safety and Toxicological Aspects

7.1 Toxicity studies

The safety and toxicity of *Nelumbo nucifera*, commonly known as lotus, have been evaluated in various studies. Research indicates that different parts of the lotus plant, including the rhizome, contain numerous bioactive compounds such as alkaloids, polyphenols, terpenoids, steroids, and glycosides, which contribute to its medicinal properties (Chen et al., 2019). However, comprehensive toxicity studies specifically focusing on the rhizome are limited. One study highlighted the potential toxicity of *N. nucifera*-derived phytochemicals, suggesting the need for further research to fully understand their safety profile (Bishayee et al., 2022). Additionally, the presence of phenolic compounds and other secondary metabolites in the rhizome has been confirmed, but their toxicological implications remain underexplored (Yamini et al., 2019a; Rani, 2019).

7.2 Safe consumption levels

The safe consumption levels of lotus rhizome have not been extensively documented. Traditional use in Asian cuisine and herbal medicine suggests that the rhizome is generally considered safe when consumed in moderate amounts. The nutritional analysis of the rhizome indicates it is a good source of carbohydrates, proteins, and other essential nutrients, supporting its use as a food ingredient (Yamini et al., 2019a). However, specific guidelines on the maximum safe intake levels are not well established. Further studies are needed to determine the appropriate consumption limits to avoid potential adverse effects.

7.3 Potential side effects

While the lotus rhizome is widely used for its health benefits, potential side effects have not been thoroughly investigated. The phytochemical composition of the rhizome includes various bioactive compounds that could potentially cause side effects if consumed in large quantities or over prolonged periods (Rani, 2019).

8 Challenges and Future Directions

8.1 Research gaps and opportunities

Despite the extensive research on the phytochemical properties and nutritional benefits of the lotus rhizome, several research gaps remain. One significant gap is the comprehensive profiling of phenolic compounds across different parts of the lotus plant. While some studies have identified a variety of phenolic compounds in lotus seeds and rhizomes, the data is still limited and fragmented (Zhu et al., 2022). Additionally, there is a lack of in-depth studies on the bioavailability and pharmacokinetics of these phytochemicals, which are crucial for understanding their therapeutic potential and efficacy (Bishayee et al., 2022). Another area that requires further exploration is the potential use of lotus rhizome byproducts and processing waste, which are rich in phenolic compounds, in various industries such as food, animal feed, and pharmaceuticals.

8.2 Technological advancements

Technological advancements in analytical techniques have significantly contributed to the identification and quantification of bioactive compounds in lotus rhizomes. Techniques such as liquid chromatography coupled with electrospray ionization quadrupole time-of-flight mass spectrometry (LC-ESI-QTOF-MS/MS) have enabled the detailed profiling of phenolic compounds (Zhu et al., 2022). High-performance liquid chromatography (HPLC) has also been instrumental in quantifying specific polyphenols in different parts of the lotus plant. However, there is still a need for the development of more advanced and cost-effective analytical methods to facilitate large-scale studies and ensure the reproducibility and accuracy of results. Additionally, advancements in extraction techniques, such as the use of green solvents and supercritical fluid extraction, could enhance the yield and purity of bioactive compounds from lotus rhizomes (Yamini et al., 2019a).

8.3 Future research directions

Future research should focus on several key areas to fully harness the potential of lotus rhizomes. Firstly, comprehensive studies on the bioavailability, pharmacokinetics, and toxicity of lotus-derived phytochemicals are essential to validate their safety and efficacy for therapeutic use (Bishayee et al., 2022). Secondly, there is a need for large-scale clinical trials to evaluate the health benefits of lotus rhizome consumption, particularly in relation to its antioxidant, anti-inflammatory, and anticancer properties. Thirdly, exploring the potential applications of lotus rhizome byproducts in various industries could provide sustainable and economically viable solutions for waste management (Zhu et al., 2022). Lastly, interdisciplinary research involving food scientists, pharmacologists, and agricultural experts could lead to the development of novel functional foods and nutraceuticals derived from lotus rhizomes, thereby enhancing their commercial value and accessibility (Ullah et al., 2018; Yamini et al., 2019a). By addressing these challenges and leveraging technological advancements, future research can unlock the full potential of lotus rhizomes, contributing to improved health outcomes and sustainable development.

9 Concluding Remarks

The comprehensive review of the phytochemical properties and nutritional benefits of the lotus rhizome (*Nelumbo nucifera*) reveals its significant potential as both a medicinal and nutritional resource. Various studies have highlighted the presence of numerous bioactive compounds, including alkaloids, polyphenols, terpenoids, steroids, and glycosides, which contribute to its diverse biological activities such as antioxidant, anti-inflammatory, immune-modulatory, antiviral, hepatoprotective, cardioprotective, and hypoglycemic effects. The rhizome, in particular, has been shown to contain high levels of phenolic compounds, which are responsible for its strong antioxidant potential. Additionally, the nutritional analysis indicates that the rhizome is a good source of carbohydrates, proteins, and essential nutrients, making it a valuable component in food production and traditional medicine.

The phytochemical and nutritional research on *Nelumbo nucifera* is crucial for several reasons. Firstly, it provides a scientific basis for the traditional use of lotus rhizome in various cultures, validating its medicinal properties and potential health benefits. Secondly, understanding the specific bioactive compounds and their mechanisms of action can lead to the development of new therapeutic agents, particularly in the prevention and treatment of chronic diseases such as cancer and diabetes. Furthermore, the identification and quantification of these compounds can enhance the commercial value of lotus byproducts, promoting their use in the food, pharmaceutical, and nutraceutical industries.

Future research should focus on several key areas to fully exploit the potential of *Nelumbo nucifera* rhizome. Firstly, more in-depth studies are needed to elucidate the molecular mechanisms underlying the bioactive compounds' effects, particularly in relation to chronic diseases such as cancer and diabetes. Secondly, there is a need for comprehensive clinical trials to confirm the efficacy and safety of lotus rhizome extracts and their isolated compounds in human populations. Additionally, exploring sustainable cultivation and processing methods can help maximize the yield and quality of bioactive compounds, making lotus rhizome a more viable commercial crop. Finally, interdisciplinary research combining phytochemistry, nutrition, and pharmacology will be essential to develop innovative applications and products derived from *Nelumbo nucifera*.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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