

Unlocking the Therapeutic Potential of *Typha angustifolia*: A Comprehensive Study of Phytochemicals, Minerals, Antibacterial Activity, and Cytotoxicity

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ABSTRACT

Typha angustifolia is an important aquatic macrophyte widely distributed in wetland ecosystems and known for its ecological, nutritional, and medicinal significance. The present study aimed to investigate the phytochemical composition, mineral profile, proximate composition, antibacterial activity, and cytotoxic potential of *T. angustifolia* leaves collected from Pakistan. Comparative analyses were performed using fresh, sun-dried, oven-dried, freeze-dried, and shade-dried samples. Solvent extraction using polar and non-polar solvents revealed higher extraction yields in polar solvents, particularly distilled water (20.13%) and methanol (18.42%), indicating the dominance of polar bioactive compounds. Proximate analysis showed that freeze-dried samples retained the highest levels of proteins, fibers, lipids, carbohydrates, and minerals, suggesting superior nutrient preservation under low-temperature drying conditions. Phytochemical screening confirmed the presence of phenolics, flavonoids, tannins, alkaloids, saponins, glycosides, and steroids, with methanolic extracts exhibiting the highest total phenolic (86.42 mg GAE/g), flavonoid (58.36 mg QE/g), and tannin content (71.24 mg TAE/g). Mineral analysis revealed potassium as the most abundant element, followed by calcium and magnesium, with freeze-dried samples showing maximum retention. Antibacterial assays demonstrated concentration-dependent inhibition against tested pathogens, with *Staphylococcus aureus* showing the highest susceptibility. Cytotoxicity evaluation indicated dose-dependent hemolytic activity against *Leishmania tropica*. Overall, the findings highlight the strong nutritional and pharmacological potential of

T. angustifolia, supporting its possible use in pharmaceutical, nutraceutical, and environmental applications.

Keywords— *Typha angustifolia*; phytochemicals; proximate analysis; mineral composition; antibacterial activity; cytotoxicity; freeze-drying.

1. Introduction

Typha angustifolia, commonly known as broadleaf cattail, is a perennial monocotyledonous, hydrophytic, and emergent aquatic macrophyte belonging to the family Typhaceae. It is widely distributed in freshwater wetlands, marshes, ponds, lakeshores, and irrigation canals across temperate and subtropical regions of the world (Nguru et al., 2022). The species thrives in shallow water and waterlogged soils, where it plays an important ecological role in nutrient cycling, sediment stabilization, and wetland ecosystem functioning (Balwan et al., 2021). Due to its rapid vegetative propagation through rhizomes and its adaptability to varying environmental conditions, *T. angustifolia* forms dense stands in aquatic habitats and contributes significantly to wetland productivity and biodiversity (Mollard et al., 2013).

Aquatic macrophytes such as *T. angustifolia* have gained increasing scientific attention because of their environmental, nutritional, and pharmacological importance. The growing global population continues to place immense pressure on food security, environmental sustainability, and healthcare systems. According to global population projections, the world population is expected to increase substantially by the end of the century, thereby increasing the demand for sustainable natural resources and alternative plant-based products. In many developing countries, staple diets are deficient in essential nutrients and bioactive compounds (Appenroth et al., 2017). Consequently, aquatic plants rich in minerals, fibers, phenolics, and secondary metabolites are being explored for their nutritional and medicinal potential (Kiran et al., 2019).

Typha angustifolia has traditionally been utilized for multiple purposes, including phytoremediation, wastewater treatment, handicraft production, animal fodder, and traditional medicine (Chakma et al., 2019). Different parts of the plant, particularly leaves, rhizomes, and pollen, contain several biologically active compounds such as phenolics, flavonoids, tannins, alkaloids, saponins, steroids, glycosides, and essential minerals (Awuchi et al., 2020). These phytochemicals are known to exhibit antioxidant, antimicrobial, anti-inflammatory, cytotoxic, and therapeutic activities (Ojelere et al., 2014). Recent studies have highlighted the potential of *T. angustifolia* as a natural source of valuable bioactive constituents that may contribute to pharmaceutical and nutraceutical applications (Sharma et al., 2025).

The increasing prevalence of antimicrobial resistance (AMR) has become a major global public health concern. The Food and Agriculture Organization (FAO) and the World Health Organization (WHO) have emphasized the importance of exploring natural plant-derived compounds as alternatives to synthetic antimicrobial agents (Angelini et al., 2024). In this regard, medicinal and aquatic plants are receiving considerable attention because they contain diverse secondary metabolites with promising antimicrobial properties. Previous investigations on *T. angustifolia* have demonstrated the presence of phenolic and flavonoid compounds associated with

inhibitory effects against several pathogenic microorganisms (Aggoun et al., 2025). Moreover, the plant is considered environmentally safe and beneficial for aquatic ecosystems due to its role in water purification and ecological restoration (Fengmin et al., 2021). In addition to its medicinal value, *T. angustifolia* is extensively used in phytoremediation because of its high capacity to absorb heavy metals, excess nutrients, and organic pollutants from contaminated water bodies (Marchand et al., 2010). Its extensive root and rhizome system facilitates the removal of pollutants and improves water quality, making it an important species in constructed wetlands and environmental management programs (Amare et al., 2022).

The present study was designed to investigate the phytochemical composition and bioactive potential of *T. angustifolia* leaves collected from Pakistan. Comparative proximate analysis, qualitative and quantitative phytochemical screening, and mineral profiling were performed on sun-dried, oven-dried, freeze-dried, and shade-dried plant samples in comparison with fresh samples. Furthermore, the phytochemical screening aimed to provide scientific evidence regarding the antimicrobial and therapeutic potential of *T. angustifolia* and its possible applications in pharmaceutical, environmental, and biotechnological fields.

2. Materials and Methods

2.1. Plant Sample Collection

Fresh samples of *T. angustifolia* were collected from freshwater wetlands and marshy areas of Islamabad during the active growing season. Healthy and disease-free leaves were selected, washed thoroughly with distilled water to remove debris and contaminants, and transported to the laboratory for further processing and analysis. Plant identification was confirmed using standard taxonomic keys and available floristic literature.

2.2. Solvent Extraction

Leaf extracts of *T. angustifolia* were prepared using Soxhlet extraction with different polar solvents, including methanol, acetone, and distilled water, as well as non-polar solvents such as chloroform and n-hexane. The extraction procedure was carried out according to the method described by Royani et al. (2025) with slight modifications. After extraction, solvents were evaporated under reduced pressure, and the percentage yield of each extract was calculated based on dry weight.

2.3. Proximate Analysis

Comparative proximate analysis of fresh and dried leaf samples of *T. angustifolia* was performed to determine moisture content, ash, crude fiber, proteins, lipids, and carbohydrates following standard AOAC procedures (Anyasor et al., 2010). Four drying techniques, namely sun-drying, oven-drying, freeze-drying, and shade-drying, were employed to prepare powdered samples. Comparative evaluation of these drying methods was conducted because drying conditions may significantly influence the nutritional composition, phytochemical stability, and bioactive constituents of aquatic plants (Omolola et al., 2020).

2.4. Qualitative and Quantitative Phytochemical Screening

Phytochemical investigations were carried out using all the prepared solvent extracts of *T. angustifolia* leaves. Standard protocols were employed for the detection of major

secondary metabolites, including phenolics, flavonoids, tannins, alkaloids, saponins, glycosides, and steroids (Patil et al., 2024). The total phenolic content (TPC) was estimated using the Folin–Ciocalteu reagent method, and absorbance was recorded at 760 nm using a UV–Visible spectrophotometer (Michiu et al., 2022). Gallic acid was used as the calibration standard. Total flavonoid content (TFC) was determined by the aluminum chloride colorimetric assay using quercetin as the standard compound, and absorbance was measured at 420 nm. Total tannin content (TTC) was quantified according to the Folin–Denis method with absorbance measured at 725 nm. Comparative analysis of extracts revealed variations in phytochemical abundance among polar and non-polar solvents.

2.5. Mineral Analysis

Mineral profiling of fresh and dried samples of *T. latifolia* was performed using atomic absorption spectrophotometry according to the method described by Perkin–Elmer analytical procedures (Athmouni et al., 2025). Essential minerals, including calcium, magnesium, potassium, sodium, iron, zinc, and manganese, were quantified to evaluate the nutritional potential of the plant.

2.6. Antibacterial Activity

The antibacterial activity of *T. angustifolia* leaf extracts was evaluated using the agar well diffusion technique described by Narakornwit et al. (2022). Four bacterial strains, namely *Salmonella typhi*, *Staphylococcus aureus*, *Escherichia coli*, and *Pseudomonas aeruginosa*, were obtained from microbial culture collections and maintained on nutrient agar media. Sterile Petri plates containing Potato Dextrose Agar (PDA) medium were inoculated with bacterial cultures using sterile cotton swabs to prepare bacterial lawns. Wells of 10 mm diameter were prepared using a sterile cork borer. Stock solutions of plant extracts were prepared in Dimethyl Sulfoxide (DMSO) at a concentration of 3 mg/mL. Different extract concentrations (25 µL, 50 µL, and 75 µL) were introduced into the wells. DMSO served as the negative control, while Ceftriaxone was used as the positive control. Plates were incubated at 37°C for 18–24 h, after which zones of inhibition were measured in millimeters. All experiments were conducted in triplicate.

$$\text{Growth Inhibition (\%)} = 100 \times \frac{(C-T)}{c} \quad (1)$$

2.7. Cytotoxicity Assay

The cytotoxic potential of *T. angustifolia* extracts was assessed against promastigote and amastigote forms of *Leishmania tropica* following the procedure described by Mehwish et al. (2019). Different concentrations of aqueous plant extracts (25, 50, 100, and 200 mg/mL) were prepared and tested. The lethal concentration (LC₅₀) values were calculated through linear regression analysis.

$$\% \text{ Hemolysis} = \frac{(\text{Sample}-\text{Control})}{\text{Control}} \times 100 \quad (2)$$

2.8. Statistical analysis

All experiments were conducted in triplicate (n = 3), and the results are expressed as mean ± standard deviation (SD). Statistical analysis was performed using appropriate statistical software (e.g., SPSS, R, or GraphPad Prism). One-way analysis of variance (ANOVA) was used to assess significant differences among drying methods, extraction

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solvents, and treatment groups.

3. Results

3.1. The Percentage yield using different solvent extracts

The extraction yield of *Typha angustifolia* leaves varied significantly among the solvents used (Table 1). Distilled water showed the highest extraction yield (20.13%), followed by methanol (18.42%) and acetone (14.76%), indicating that polar solvents were more efficient in extracting bioactive compounds from the plant material. The higher extraction efficiency of polar solvents may be attributed to the abundance of polar phytochemicals, including phenolics, flavonoids, tannins, glycosides, and carbohydrates, in *T. angustifolia*. In contrast, non-polar solvents, including chloroform and n-hexane, exhibited comparatively lower extraction yields, suggesting a lower abundance of non-polar constituents such as lipids and waxes in the plant leaves. Among the non-polar solvents, chloroform showed a relatively higher yield than n-hexane. Overall, the findings indicate that *T. angustifolia* leaves are rich in polar bioactive compounds and possess considerable phytochemical potential.

Table 1: Comparative Evaluation of Polar and Non-Polar Solvent Extraction from *T. angustifolia*

Solvent Used	Nature of Solvent	Percentage Yield (%)
Methanol	Polar	18.42 ± 0.54
Acetone	Polar	14.76 ± 0.41
Distilled Water	Polar	20.13 ± 0.63
Chloroform	Non-polar	9.25 ± 0.28
n-Hexane	Non-polar	6.81 ± 0.19

3.2. Proximate analysis

The proximate composition of *T. angustifolia* leaves demonstrated considerable variation among fresh and differently dried samples (Table 2). Fresh samples exhibited the highest moisture content (78.45%), whereas freeze-dried samples retained the lowest moisture level (4.12%), indicating greater dehydration efficiency of freeze-drying compared to other drying techniques. Reduced moisture content is beneficial for prolonging shelf life and minimizing microbial deterioration. Ash content, which represents total mineral composition, was highest in freeze-dried samples (11.34%), suggesting better preservation of inorganic constituents during freeze-drying. Similarly, freeze-dried samples showed the highest crude fiber (21.45%), protein (15.61%), lipid (4.52%), and carbohydrate contents (38.92%). This may be attributed to minimal thermal degradation and improved retention of nutrients during the freeze-drying process. Sun-dried and shade-dried samples also retained appreciable nutritional values; however, oven-dried samples exhibited slightly reduced nutrient contents, possibly due to exposure to elevated temperatures, leading to degradation of heat-sensitive compounds. Overall, freeze-drying appeared to be the most effective drying method for preserving the nutritional quality and biochemical constituents of *T.*

angustifolia leaves.

Table 2: Assessment of Proximate Constituents of *T. angustifolia*

Parameters (%)	Fresh Sample	Sun-dried	Oven-dried	Freeze-dried	Shade-dried	Parameters (%)
Moisture Content	78.45 ± 1.12	9.62 ± 0.21	6.84 ± 0.18	4.12 ± 0.09	8.35 ± 0.17	Moisture Content
Ash Content	8.14 ± 0.24	10.25 ± 0.31	9.82 ± 0.28	11.34 ± 0.36	10.74 ± 0.33	Ash Content
Crude Fiber	18.62 ± 0.47	20.13 ± 0.55	19.86 ± 0.51	21.45 ± 0.63	20.74 ± 0.58	Crude Fiber
Crude Protein	12.35 ± 0.36	14.22 ± 0.41	13.78 ± 0.39	15.61 ± 0.44	14.96 ± 0.42	Crude Protein
Crude Lipids	3.82 ± 0.11	4.24 ± 0.13	3.91 ± 0.10	4.52 ± 0.14	4.13 ± 0.12	Crude Lipids
Carbohydrates	32.74 ± 0.92	36.48 ± 1.03	35.81 ± 0.96	38.92 ± 1.14	37.16 ± 1.08	Carbohydrates

3.3. Phytochemical analysis

Qualitative phytochemical screening of *T. angustifolia* leaf extracts revealed the presence of several important secondary metabolites, including phenolics, flavonoids, tannins, alkaloids, saponins, glycosides, and steroids. The distribution and abundance of these phytochemicals varied depending on the solvent polarity used during extraction. Polar solvents, particularly methanol and distilled water, demonstrated higher extraction efficiency for phenolics, flavonoids, tannins, saponins, and glycosides. Methanolic extracts showed a strong presence of phenolics, flavonoids, and tannins, whereas aqueous extracts contained the highest amount of saponins and glycosides. This indicates that most bioactive constituents in *T. angustifolia* leaves are polar in nature. In contrast, non-polar solvents such as chloroform and n-hexane extracted relatively lower quantities of phytochemicals. Steroids were comparatively more detectable in chloroform and n-hexane extracts due to their nonpolar chemical characteristics (Table 3). Overall, the findings suggest that *T. angustifolia* is rich in biologically active phytochemicals with potential medicinal and pharmacological applications.

Quantitative phytochemical analysis (Table 4) demonstrated significant differences in the concentrations of phenolics, flavonoids, and tannins among the different solvent extracts of *Typha angustifolia*. Methanolic extract exhibited the highest total phenolic content (86.42 mg GAE/g), flavonoid content (58.36 mg QE/g), and tannin content (71.24 mg TAE/g), indicating that methanol was the most effective solvent for extracting phytochemicals from the plant leaves. Aqueous extracts also showed substantial amounts of bioactive compounds, confirming the presence of water-soluble secondary metabolites in *T. angustifolia*. Acetone extracts displayed moderate phytochemical concentrations, whereas chloroform and n-hexane extracts exhibited considerably lower values. The reduced extraction efficiency of nonpolar solvents suggests that most phytochemicals in *T. angustifolia* are polar. The elevated phenolic and flavonoid contents observed in the methanolic and aqueous extracts may contribute

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to the plant's antioxidant, antimicrobial, and therapeutic properties. These findings support the potential use of *T. angustifolia* as a natural source of bioactive compounds for pharmaceutical, nutraceutical, and medicinal applications.

Table 3. Qualitative Phytochemical Screening of Different Solvent Extracts of *T. angustifolia* Leaves

Phytochemicals	Methanol	Acetone	Distilled Water	Chloroform	n-Hexane
Phenolics	+++	++	+++	+	+
Flavonoids	+++	++	++	+	-
Tannins	+++	++	+++	+	-
Alkaloids	++	++	+	+	-
Saponins	++	+	+++	-	-
Glycosides	++	++	+++	+	-
Steroids	+	+	+	++	++

Table 4. Quantitative Phytochemical Analysis of *T. angustifolia* Leaf Extracts

Solvent Extract	Total Content GAE/g	Phenolic (mg)	Total Content (mg QE/g)	Flavonoid	Total Content TAE/g	Tannin (mg)
Methanol	86.42 ± 2.14		58.36 ± 1.72		71.24 ± 1.95	
Acetone	68.75 ± 1.88		46.18 ± 1.36		59.42 ± 1.63	
Distilled Water	79.31 ± 2.06		52.44 ± 1.58		66.87 ± 1.81	
Chloroform	34.52 ± 1.12		22.63 ± 0.84		28.46 ± 0.91	
n-Hexane	21.84 ± 0.76		14.35 ± 0.52		18.27 ± 0.67	

3.4. Mineral composition

Mineral analysis of *T. angustifolia* leaves demonstrated the presence of several essential macro- and micronutrients, including calcium, magnesium, potassium, sodium, iron, zinc, and manganese (Table 5). Significant variations in mineral concentrations were observed among fresh and differently dried samples, indicating that drying methods influence mineral retention and concentration. Among all analyzed minerals, potassium was detected in the highest concentration across all samples, followed by calcium and magnesium, suggesting that *T. angustifolia* is a rich source of essential macronutrients important for metabolic and physiological functions. Freeze-dried samples exhibited the highest concentrations of nearly all minerals, including calcium (218.74 mg/100 g), potassium (368.45 mg/100 g), and iron (17.95 mg/100 g). This enhanced mineral retention may be attributed to the low-temperature dehydration process of freeze-drying, which minimizes nutrient degradation and preserves biochemical integrity. Sun-dried and shade-dried samples also retained appreciable mineral levels, whereas

oven-dried samples showed slightly reduced mineral concentrations, possibly due to thermal losses or structural changes occurring during high-temperature drying. Fresh samples generally exhibited comparatively lower mineral values because of their higher moisture content, which dilutes nutrient concentration. The presence of iron, zinc, and manganese in considerable amounts highlights the nutritional and therapeutic importance of *T. angustifolia*. These minerals play vital roles in enzymatic reactions, antioxidant defense systems, immune function, and hematopoiesis. Overall, the results suggest that *T. angustifolia* possesses significant nutritional value and may serve as a potential natural source of essential minerals for pharmaceutical, nutraceutical, and dietary applications.

Table 5. Mineral Composition of Fresh and Differently Dried Samples of *Typha angustifolia* Leaves

Minerals (mg/100 g)	Fresh Sample	Sun-dried	Oven-dried	Freeze-dried	Shade-dried
Calcium (Ca)	182.45 ± 4.36	201.62 ± 5.14	194.31 ± 4.88	218.74 ± 5.62	209.18 ± 5.27
Magnesium (Mg)	96.28 ± 2.43	108.54 ± 2.86	103.71 ± 2.65	115.92 ± 3.04	111.43 ± 2.91
Potassium (K)	324.17 ± 7.85	351.24 ± 8.42	342.63 ± 8.11	368.45 ± 9.04	359.12 ± 8.76
Sodium (Na)	72.35 ± 1.96	79.48 ± 2.14	76.92 ± 2.03	84.16 ± 2.28	81.73 ± 2.19
Iron (Fe)	14.63 ± 0.41	16.24 ± 0.48	15.82 ± 0.44	17.95 ± 0.52	17.11 ± 0.49
Zinc (Zn)	5.26 ± 0.16	6.14 ± 0.18	5.92 ± 0.17	6.73 ± 0.20	6.41 ± 0.19
Manganese (Mn)	3.84 ± 0.11	4.28 ± 0.13	4.12 ± 0.12	4.67 ± 0.14	4.45 ± 0.13

3.5. Antibacterial activity

The antibacterial activity of *T. angustifolia* leaf extracts demonstrated concentration-dependent inhibition against all tested bacterial strains (Figure 1). The highest antibacterial effect was observed at 75 µL concentration, particularly against *Staphylococcus aureus* with a maximum inhibition zone of 24 mm. Moderate activity was recorded against *Salmonella typhi* and *Escherichia coli*, whereas *Pseudomonas aeruginosa* showed comparatively lower susceptibility. The increase in inhibition zones with increasing extract concentration indicates the presence of potent bioactive compounds with antimicrobial potential.

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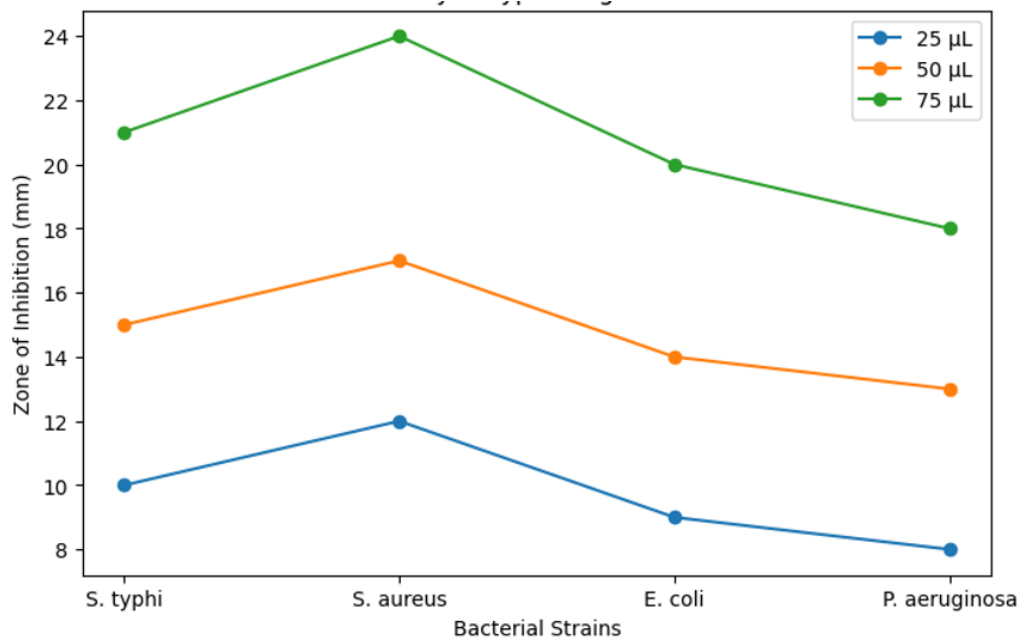
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Figure 1. Concentration-dependent antibacterial activity of *T. angustifolia* leaf extracts against selected bacterial strains, showing maximum inhibition at 75 µL, particularly against *Staphylococcus aureus*.

3.6. Cytotoxicity Assay

The cytotoxicity assay of *T. angustifolia* extracts against *Leishmania tropica* revealed a dose-dependent increase in hemolytic activity (Figure 2). Lower extract concentrations showed mild cytotoxic effects, while higher concentrations produced greater hemolysis. The maximum hemolytic activity was observed at a 200 mg/mL concentration. These findings suggest that the plant extracts possess biologically active compounds capable of exerting cytotoxic effects, which may contribute to their pharmacological potential.

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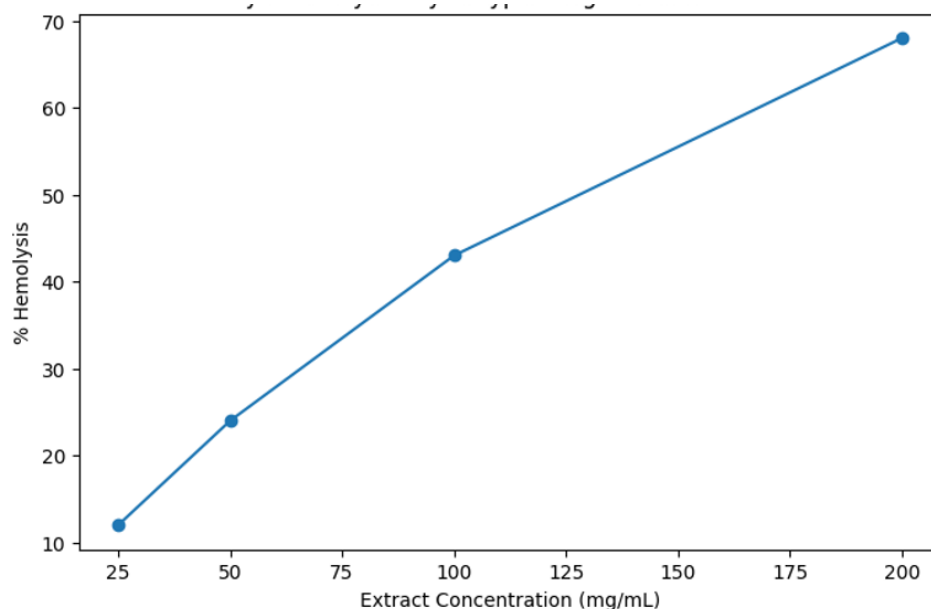
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Figure 2. Antiparasitic activity of the *T. angustifolia* leaves extract

4. Discussion

The present investigation provides a comprehensive evaluation of the phytochemical profile, mineral composition, proximate constituents, antibacterial activity, and cytotoxic potential of *Typha angustifolia*, thereby highlighting its multifaceted therapeutic and nutritional significance. Aquatic macrophytes have increasingly been recognized as valuable reservoirs of bioactive compounds, particularly in the context of rising antimicrobial resistance and nutritional deficiencies in developing regions (Appenroth et al., 2017; Shahi et al., 2026). The findings of this study strongly support the view that *T. angustifolia* is a functionally important plant with considerable pharmaceutical and nutraceutical potential. The observed variation in extraction yield among different solvents clearly indicates that solvent polarity plays a crucial role in determining extraction efficiency. Polar solvents, particularly distilled water and methanol, exhibited significantly higher yields compared to non-polar solvents. This trend suggests that *T. angustifolia* leaves are predominantly rich in polar phytoconstituents such as phenolics, flavonoids, tannins, glycosides, and carbohydrates. Similar findings have been reported in other medicinal aquatic plants, where polar solvents effectively extract hydrophilic bioactive compounds (Aggounet al., 2025).

Quantitative phytochemical analysis further confirmed that methanolic extracts contained the highest concentrations of total phenolics, flavonoids, and tannins. These compounds are well known for their antioxidant, antimicrobial, and cytoprotective properties (Yadav et al., 2025). The elevated phenolic content in *T. angustifolia* suggests strong radical scavenging potential, which may contribute to its observed antibacterial activity. Phenolic-rich plants have been widely documented to exhibit inhibitory effects against pathogenic microorganisms through disruption of microbial membranes and inhibition of enzyme activity (Anju et al., 2023). Drying methods

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significantly influenced the proximate composition of *T. angustifolia* leaves. Freeze-drying was found to be the most effective technique for preserving moisture-sensitive nutrients, including proteins, lipids, carbohydrates, and minerals. This may be attributed to the low-temperature dehydration process, which minimizes enzymatic degradation and thermal breakdown of nutrients (ElGamal et al., 2023). In contrast, oven-drying resulted in comparatively reduced nutrient retention, likely due to heat-induced degradation of thermolabile compounds.

The high ash content in freeze-dried samples indicates better retention of inorganic minerals, which are essential for physiological functions such as enzyme activation, osmoregulation, and bone formation (Gunya et al., 2016). Similar patterns have been observed in other edible aquatic plants, where freeze-drying preserved biochemical integrity more effectively than conventional drying methods (Rezania et al., 2019). These results emphasize the importance of post-harvest processing techniques in determining the nutritional value of medicinal plants. Mineral analysis revealed that *T. angustifolia* is a rich source of essential macro- and micronutrients, particularly potassium, calcium, and magnesium. Potassium was the most abundant element, indicating its potential role in maintaining electrolyte balance and cardiovascular health. Calcium and magnesium are essential for bone metabolism, neuromuscular function, and enzymatic regulation (Binesh et al., 2026). The presence of iron, zinc, and manganese further enhances the nutritional value of the plant, as these trace elements are vital for hematopoiesis, immune function, and antioxidant defense systems (Kaur, et al., 2023). Freeze-dried samples exhibited the highest mineral concentrations, which may be attributed to reduced leaching and minimal structural degradation during processing. These findings are consistent with previous studies reporting that gentle drying methods preserve mineral integrity more effectively than high-temperature treatments (Ray et al., 2013). Thus, *T. angustifolia* may serve as a natural dietary supplement for addressing micronutrient deficiencies in human nutrition.

The antibacterial evaluation demonstrated a clear concentration-dependent inhibitory effect of *T. angustifolia* extracts against all tested bacterial strains. The highest susceptibility was observed in *Staphylococcus aureus*, while *Pseudomonas aeruginosa* exhibited comparatively lower sensitivity. This variation in response may be attributed to differences in bacterial cell wall structure and permeability (Murínová et al., 2014). The strong antibacterial activity can be linked to the presence of phenolic compounds, flavonoids, and tannins, which are known to exert antimicrobial effects through multiple mechanisms, including membrane disruption, enzyme inhibition, and metal ion chelation (Nassarawa et al., 2023). Gram-positive bacteria are generally more susceptible to plant extracts due to the absence of an outer lipopolysaccharide membrane, which is present in Gram-negative bacteria such as *P. aeruginosa* (Voukeng et al., 2026). These findings support the potential use of *T. angustifolia* as a natural antimicrobial agent in pharmaceutical applications.

The cytotoxicity assay revealed dose-dependent hemolytic activity of *T. angustifolia* extracts against *Leishmania tropica*. The increasing cytotoxic effect with higher concentrations suggests the presence of bioactive compounds capable of disrupting cellular integrity. Plant-derived secondary metabolites, particularly saponins and alkaloids, are known to exhibit antiparasitic and cytotoxic properties (Ibrahim et al.,

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2026). While cytotoxic activity may indicate therapeutic potential against parasitic infections, it also necessitates careful toxicological evaluation to ensure biosafety. Similar dual bioactivities have been reported in other medicinal plants, where therapeutic benefits are accompanied by potential cytotoxic risks at higher doses (Shakeel et al., 2025). Therefore, further in vivo studies are required to establish safe dosage ranges and pharmacological applicability. Overall, the integrated analysis of phytochemical, nutritional, antimicrobial, and cytotoxic properties demonstrates that *T. angustifolia* is a multifunctional plant with significant biological potential. Its richness in phenolic compounds and essential minerals, combined with notable antibacterial activity, positions it as a promising candidate for drug development and functional food applications. Moreover, its role in environmental systems, including phytoremediation and wetland stabilization, further enhances its ecological value (Bhatia et al., 2014).

5. Conclusion

The present study demonstrates that *T. angustifolia* leaves possess significant nutritional, phytochemical, antibacterial, and cytotoxic properties, highlighting their potential value for pharmaceutical, nutraceutical, and environmental applications. The findings clearly indicate that drying methods strongly influence the preservation of bioactive compounds, with freeze-drying proving most effective in retaining proteins, fibers, lipids, carbohydrates, and essential minerals. Phytochemical analysis confirmed the richness of *T. angustifolia* in phenolics, flavonoids, tannins, alkaloids, saponins, glycosides, and steroids, with methanolic extracts exhibiting the highest bioactive compound yield. The strong antioxidant-related phytochemicals were closely associated with notable antibacterial activity, particularly against *Staphylococcus aureus*, indicating their potential as a natural antimicrobial agent. Furthermore, the observed dose-dependent cytotoxic (hemolytic) activity against *Leishmania tropica* suggests possible antiparasitic relevance, although further in-depth toxicological evaluation is required to ensure safety. Mineral profiling also revealed *T. angustifolia* as a rich source of essential nutrients, particularly potassium, calcium, and magnesium. Overall, *T. angustifolia* emerges as a promising aquatic macrophyte with substantial biofunctional potential. Optimization of extraction and preservation methods can further enhance its applicability in drug development, functional foods, and environmental biotechnology.

Authors contribution

M.S.H.: Conceptualization, Research design, Experiments, Methodology, Project administration, Formal analysis, Writing and drafting; **N.A.:** Experimentation, Validation, Software, Writing – review & editing, Visualization, Data Curation; **H.S.:** Formal analysis, Writing – review & editing; **F.B.:** Investigation, Methodology, Data curation, Validation, Review, Writing – review & editing. All authors have read and agree with the final version of the manuscript.

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Competing interest

Authors have no competing interests

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Conflict of interest

All authors declare no conflict of interest

Consent to participate

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