International Research Journal of Multidisciplinary Scope (IRJMS), 2025; 6(1):927-937 IRJMS

Review Article | ISSN (O): 2582-631X DOI: 10.47857/irjms.2025.v06i01.02931

Unveiling the Therapeutic Potential of Hydrocharitaceae Family: A Review of Phytochemistry and Pharmacology

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Abstract

The global rise of diseases due to many microorganisms including multidrug-resistant (MDR) bacteria which poses a significant threat to public health, with nosocomial infections often linked with these resilient pathogens. Moreover, MDR bacteria are increasingly causing illnesses within the community, leading to heightened rates of morbidity, mortality, healthcare expenditure, and antibiotic consumption. Across cultures worldwide, the utilization of medicinal plants for health benefits dates back to ancient times, showcasing humanity's profound understanding of their therapeutic properties through observation and experimentation. *Hydrilla verticillata*, a member of the Hydrocharitaceae family, possesses noteworthy nutraceutical and pharmacological attributes, yet many other species within this family have remained underexplored for decades. Thus, there is a pressing need to comprehensively explore the bioactive compounds present in these plants and their diverse applications across various fields. Phytomedicines, derived from medicinal plants, represent a primary approach for treating various ailments, harnessing a plethora of secondary metabolites and bioactive substances for therapeutic purposes. Many ethnomedicinal plant products offer a safe, cost-effective alternative with minimal side effects, prompting a shift in focus within the pharmaceutical industry towards herbal medications. Furthermore, some tribal communities have long recognized the medicinal potential of aquatic macrophytes, further expanding the scope of natural sources for medicine.

Keywords: *Hydrilla,* Hydrocharitaceae, Nanoparticle, Pharmaceuticals, Phytol.

Introduction

Brief overview of Hydrocharitaceae

The family Hydrocharitaceae is an utterly aquatic monocot with a worldwide distribution that comprises 18 genera along with roughly 120 species. The family inhabits both freshwater and marine environments, and it is an integral component of aquatic ecosystems. It exhibits various forms and habits, such as free-floating, rooted floating and partially submerged (1, 2). It contains numerous useful aquarium plants, and certain species, like *Elodea canadensis* and *Hydrilla verticillata*, provide habitats for fish and feed for the chicken-raising industry (3). Some species, including *Ottelia alismoides* and *Blyxa japonic,* are threatened due to habitat demolition and a progressive expansion in commercial maritime activities. Other species, like *Hydrilla verticillata*, have become invasive weeds of tremendous concern (4). The majority of Hydrocharitaceae species are unisexual, while a few are hermaphrodites. Hermaphroditism is considered the original condition that produces unisexual flowers (5).

Historical uses of Some Important Species of the Hydrocharitaceae Family in Traditional Medicine

Most species in this family have antimicrobial and nutritional properties. *Hydrocharis dubia* (Blume) Backer, *Ottelia alismoides* (L.) Pers. and *Blyxa echinosperma* (C.B. Clarke) Hook.f. are used as a digestive tonic in traditional medicine in Southeast Asia, India, and China (6). *Ottelia alismoides* treats asthma, peeing difficulties, hydrops, skin problems, and burns. It also has antituberculosis properties (7). *Hydrilla verticillata* is well-known to boost neurological health, circulation, bodily resistance, gastrointestinal function, and endurance (8). Hydrilla has medicinal and nutraceutical properties, such as vitamin B12, zinc, and selenium, and a higher concentration of calcium (9). It acts as antioxidants and also a powerful

(Received 23rd October 2024; Accepted 27th January 2025; Published 31st January 2025)

immunological support for humans. *Stratiotes aloides* L. is employed to treat kidney and wound injuries (10). Antimicrobial activity is detected in *Enhalus acoroides* (11).

The Increasing Global Concern about Microbial Threats and the Need for Alternative Antimicrobial Agents

Antimicrobial resistance (AMR) is a global issue that has become increasingly prevalent and significantly impacted our society. AMR made conventional drugs ineffective against microbes and made diseases incurable. Medicines derived from plants are believed to be safer substitutes for manufactured medications. These natural remedies' ingredients and blends have been used for millennia because they are easily accessible, affordable, and have relatively few adverse effects. The secondary metabolites in aromatic plants make to defend themselves against microbes are called essential oils (EOs). Nonetheless, these EOs and their constituents have shown significant anti-drug resistance in microorganisms. Compared to medicines, these oils are highly efficient antibacterial agents. Additionally, the efficacy of synthetic medications is increased when EOs or their components are added. Therefore, natural extracts (EOs) can be utilized as an alternative to manufactured antimicrobial agents in combating resistant strains of pathogenic microbes. EOs can interact with various target sites, including the cytoplasmic membrane, the efflux pump, protein synthesis, etc. (12). Increasing antibiotic resistance diseases influence virtually every aspect of contemporary medicine and threaten the effectiveness of numerous medical advances, including cancer treatment, organ donation, and surgery (13-20). Nosocomial infections, such as bloodstream infections and pneumonia, are frequently caused by *Pseudomonas aeruginosa*. It is found in various sites within the hospital, including sink traps, aerators, and other equipment such as scopes, breathing apparatus, and poisonous solutions (21-23). Urinary tract infections and bacterial infections are among various community-associated infections that Enterobacteriaceae frequently cause. Unfortunately, unlike the circumstances mentioned for *P. aeruginosa*, there is significant resistance in isolates of community-associated Enterobacteriaceae (24). Hypervalent reactions in strains of *Klebsiella pneumoniae* are a severe issue throughout Asia. These "hypermucoviscous" strains are known to cause meningitis and pyogenic liver abscesses frequently (25). The main reasons for resistance to drugs may be the control of biofilm and mutation in bacteria. Nanomaterials and plant extract as antibacterial supplements are very promising and draw much interest in controlling these bacteria, as they may cover gaps where antibiotics frequently fall short (26, 27). Presently antimicrobial nanoparticles (NPs) such as metal, metal oxide, and organic nanoparticles, along with antibiotic function, use two main lethal pathways that are linked to each other and often arise at the same time: disrupting membrane potential and integrity, and generation of reactive oxygen species (ROS). Here, nanoparticles serve as nanocatalysts (28, 29). Plant screening is currently in progress as an alternative source for antibacterial drugs, and all the secondary metabolites contribute to retaining the curative properties in plants. Some secondary metabolites are believed to give plants their antimicrobial qualities. The peptides that comprise plant defense systems are another form of antimicrobial agents; they are identical in structure to human antimicrobial peptides. The following is an overview of the extensive discussions on the different plant-active chemicals in the Hydrocharitaceae family that have therapeutic properties. Benzoquinones, which are composed of two isomers of cyclohexadienedione, are examples of molecules having a wholly conjugated cyclic dione structure that are classified as quinones, and they also have antibacterial activity against *Pseudomonas aeruginosa* 30. Also exhibited broad and specific antibacterial efficacy against methicillin-sensitive and methicillin-resistant strains of Staphylococcus (30- 32). A comprehensive exploration of this family requires a multidisciplinary approach, integrating various fields of study to unveil the full spectrum of their medicinal potential along with the molecular analysis of species of the Hydrocharitaceae family. A deep investigation is needed to evaluate the pharmacological properties of Hydrocharitaceae species, unlocking valuable insights that could contribute to advancements in medicine and drug discovery.

The Purpose of the Review is to Examine Hydrocharitaceae's Potential

The study aims to gather the recent developments of the members of this family, including the traditional uses of the important species for future reference and research. Amongst all the species, *Hydrilla* of the hydrocharitaceae family has tremendous nutraceutical properties with high amounts of vitamins, macro and micronutrients and is also recognised for its rich source of calcium. Though many of the species of this family have great value in terms of nutraceutical and pharmaceutical properties, many species are yet to be validated scientifically. Presently, the world depends on natural products as a source of nutrients and medicine to avoid unwanted side effects of synthetic medicine. So, for this approach, a salient study is done to explore more about the phytoconstituent present in these species of the family Hydrocheritacea and their medicinal value.

Sustainable Harvesting Practices of Threatened Species of Hydrocharitacea

To ensure the long-term conservation and sustainable use of *Ottelia alismoides* and *Blyxa japonica*, a comprehensive strategy involving research, sustainable practices, conservation efforts, community involvement, policy development, scientific collaboration, and continuous monitoring is essential. Research and monitoring should focus on assessing population distribution, ecological requirements, and threats like habitat loss, pollution, invasive species, and overharvesting. Sustainable harvesting practices, including regulated and selective harvesting with eco-friendly techniques, should be implemented to prevent depletion. Conservation efforts must prioritize habitat protection, restoration of aquatic ecosystems, and ex-situ conservation measures such as seed banks and nurseries for propagation. Community involvement is vital, with awareness campaigns educating stakeholders on sustainable practices and fostering community-based management. Policy and regulation are necessary to enforce legal protection, regulate trade, and include these species in conservation frameworks like the IUCN Red List or CITES. Scientific collaboration can enhance conservation strategies through shared research and best practices. Finally, long-term monitoring and evaluation are crucial to measure the effectiveness of these efforts and adapt strategies based on emerging challenges and updated data.

Discussion

Key Bioactive Compounds Present in Hydrocharitaceae with Potential Antimicrobial Properties

The chemical component in the form of secondary metabolites significantly impacts its bioactivity. The *Hydrilla* species (Figure 1) is an exotic aquatic species that is fragile and immersed and a member of the Hydrocharitaceae family. It is commonly referred to as a superfood because of its rich supply of nutrients, such as vitamins and minerals for aquatic animals, which are also utilized to create biogas and formulated fish feed. Aqueous extract of *Hydrilla verticillate* has excellent medicinal properties, such as causing depressive action in the central nervous system (CNS). Additionally, it contains antimicrobial and anti-cancer bioactive compounds, which are proven in *in vitro* conditions (33).

Phytoconstituents in *Hydrilla* vercillata (L.F.) Royle and Applications

Researchers indicate that *H. verticillata* contains numerous volatile components. *H. verticillata* extracts macerated in PE: acetone contained Pythol and 3,5,11,15-tetramethyl-1-hexadecen-3-ol as main compounds (34). Soxhletation extract with ethanol solvent contains diterpene (Phytol), Coryan-17-ol-18, 19-didehydro-10-methoxy-acetate, and Ergost-5-en-3-ol, 22,23-dimethyl-acetate, pentadecanoic acid-14-methyl, methyl ester, linoleic compound (10-octadecenoic acid, methyl ester) and 1,2-benzene dicarboxylic acid butyl octyl ester (35). *Hydrilla verticillata* contains ost-5-en-3-ol and 22,23-dimethyl-acetate, which can inhibit MMP-2 and MMP-9 enzymes. This chemical falls within the category of steroids. Steroid chemicals are intensively explored for their cytotoxic action (36, 37). *Hydrilla verticillata* (L.f.) Royle extracts were tested against five pathogenic bacteria "*Enterococcus faecalis, Escherichia coli, Klebsiella pneumoniae, Shigella flexneri, and Vibrio choleriae"* using agar well diffusion and DPPH scavenging assays for antioxidant activity. *H. verticillata* inhibited all the pathogens, showing a clear highest zone of inhibition against *Shigella flexneri* and the lowest zone of inhibition against *Klebsiella pneumonia* (38). A natural bidirectional diterpene fatty

alcohol called phytol is present in Hydrilla verticillata. This compound can produce 0.1–1.0 metric tons yearly worldwide and is a precursor to vitamins E, and K. Phytol sulfate exhibited good sterilizing efficiency because of its antibacterial impact on surface bacteria (39). Several antioxidant and antibacterial properties have been found in *H. verticillata*, along with anticancer, antimalarial, antiaging, detoxifying, and anti-inflammatory properties (33, 40). *H. verticillata* possesses a broad spectrum of metabolite compounds, which include steroids, alkaloids, flavonoids, saponins, and triterpenoids (41). Secondary metabolites called steroids have particular functions. For example, the algae extract from Tydemnia expeditions includes steroids, which might prevent prostate cancer from proliferating (42, 43). The significance of isolating steroid compounds from *H. verticillata* might originate from their potential as drugs.

Phytoconstituents in *Thalassia testudinum* K.D.Koenig and Applications

Thalassia testudinum contains elevated phenolic acid concentration, and this phenolic acid is the main reason for preventing labyrinthula growth. Labyrinthula is a heterotrophic protist believed to grow in the root of marine grasses, creating a disease that spreads the slime net extracellular network. It was reported that endophytic fungi in the *Thalassia testudinum* are responsible for maintaining elevated concentrations of four compounds such as 3,4-dihydroxybenzoic acid, p-hydroxybenzoic acid, p-coumaric acid. These derivatives of phenolic compounds inhibit the growth of Labrynthula (44, 45).

Phytoconstituents in *Halophila stipulacea* and Applications

Halophila stipulacea extracts displayed cytotoxicity, lipid-reducing, and antifouling capabilities. In phytochemical profiling using mass spectroscopy and GNPS, some important phytoconstituent are identified, such as apigenin, lueolin, polyphenol (Cirsimarin, 2,4-dihydroxyheptadec-16-ynyl acetate, spiraeoside) and matairesinol, fatty acids like 13-decosenamide; cinnamic acids: 3-hydroxy-4-methoxycinnamic acid, alpha-cyano-4-hydroxycinnamic, N-acetyl-L-tyrosine. These phytocompounds are supposed to fight against cancer and metabolic disorders. Also, they act as an antifouling agent (46).

Phytoconstituents in *Vallisneria spiralis* L. and Applications

Despite being utilized as a refrigerant and for skin lotions, *Vallisneria spiralis* L. was found to have antifungal properties against *Dandruff dermitis*. When 80% ethanol was tested for probable biochemical analysis, it demonstrated an intriguing co-linearity in the phenol and antioxidant peaks, indicating that the antioxidant molecule is phenolic in origin (47, 48).

Phytoconstituents in *Enhalus acoroides* and Applications

Nonadecene and n-tetracosanol are the two most essential phytocompounds identified in *Enhalus acoroides*. Nonadecene, a long-chain fatty acid, was shown to have antifungal and antituberculosis actions. An alcoholic compound called n-Tetracosanol-1 can show antibacterial properties (48, 49). Antioxidant properties have been identified in butylated hydroxytoluene and phenol-4-2-(aminomethyl)-4-thiazolyl might be synthesized through the use of "phenol-2,6-bis(1,1-dimethylethyl)-4, methyl carbamate.2,6-bis(1,1-dimethylethyl) monohydrochloride", which has significant therapeutic use for Huntington's disease (50). The tetracyclic triterpenoid lanosterol is the precursor of steroid molecules. The oxidation process can be utilized to create derivatives of lanosterol and cholesterol (51). This suggests that, in the intact cell, oxysterols might function as natural regulators of cholesterol biosynthesis. Among the phytochemicals that have been found, hemolytic 5-alpha is a reductase inhibitor, n-hexadecanoic acid, Hexadecanoic acid, and ethyl ester have antioxidant, hypocholesterolemic, nematicide, pesticide, and lubricant actions (52).

Phytoconstituents in *Pistia stratiotes* and Applications

Pistia stratiotes leave, and roots possess n-Hexadecanoic acid as a common ingredient. The ethyl ester of E-11-Hexadecanoic acid has antifungal, antitumor, and antibacterial properties. It was found that linolenic acid methyl ester exhibited hepatoprotective, nematocides, hypocholesterolemic, and anti-arthritic characteristics. Ethyl isoallocholate is believed to be a sterol molecule with potential applications as a pesticide, antibacterial, antioxidant, anticancer, and cancer-preventative agent (53). Numerous biological properties, such as anti-inflammatory,

anti-tumor, hepatoprotective, antimicrobial, anti-arthritic, antioxidant, anti-diabetic, anti-coronary, anti-eczemic, anti-acne, 5-alpha reductase inhibitor, and anti-androgenic have been reported for 1-monolinoleoylglycerol trimethylsilyl ether, 9, 12, 15-Octadecatrienoic acid, methyl ester, (Z, Z, Z)-is a polyenoic fatty acid compound 52-53. Diisooctyl phthalate is a plasticizer compound with antibacterial and antifouling abilities (54).

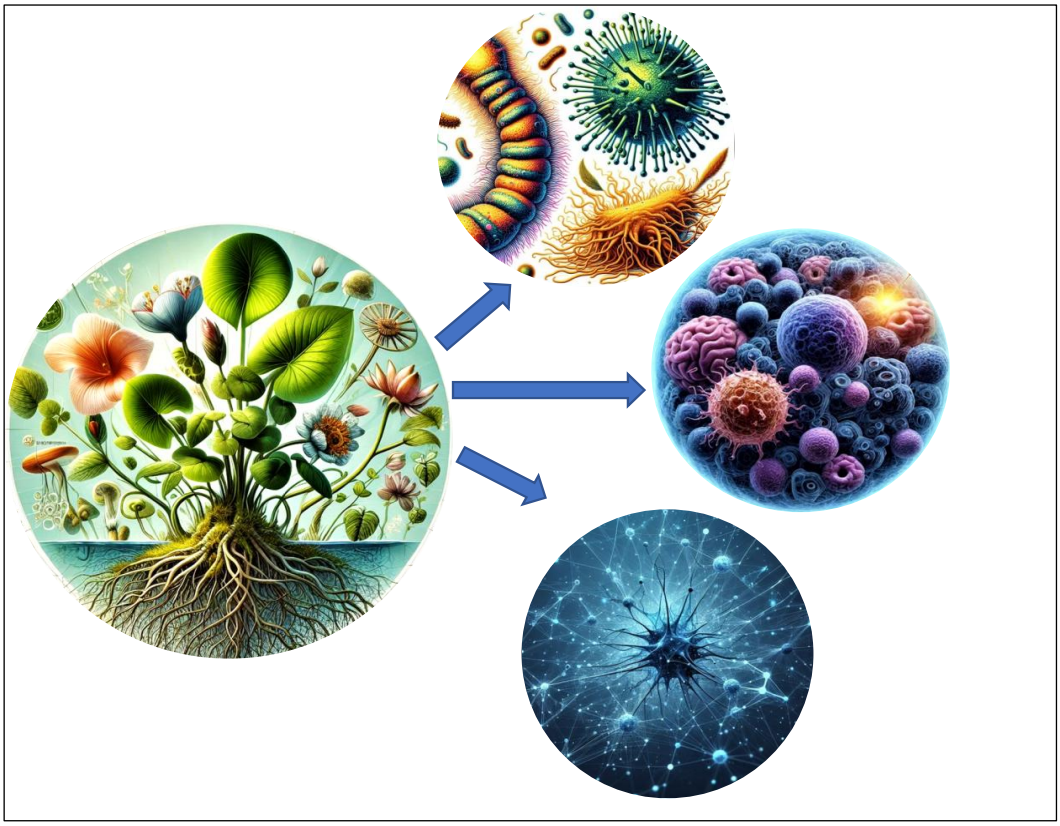

Figure 1: Different Available Approaches to Tackle the Microbes and other Diseases Using the Bioactive Compounds from Species of *Hydrocharitaceae* Family

Several species from the Hydrocharitaceae family have demonstrated notable pharmacological activities. *Ottelia alismoides* is recognized for its antimicrobial, anti-inflammatory, and antioxidant properties, making it valuable in treating infections and skin diseases. *Hydrilla verticillata* exhibits antioxidant, anti-diabetic, and antimicrobial activities, with potential applications in managing oxidative stress and diabetes (55). *Enhalus acoroides* is traditionally used for wound healing and as a remedy for infections, owing to its antimicrobial, anti-inflammatory, and anti-cancer properties (Table 1). Many of these species have demonstrated pharmacological activities in studies, the extent of their efficacy, safety, and mechanisms of action may require further research and clinical validation. Conservation efforts are also important to ensure the sustainable use of these resources.

Table 1: List of Species from Hydrocharitaceae Family having Pharmacological Activity

Sl. No	Species Name	Parts Used	Phytochemical Present	Antimicrobial	Functional groups	References
1	*Hydrilla verticillata*	Leaf, stem, flowers	Alkaloid, phenols, flavonoids, saponins, Terpeniods (Ethanolic extracts-Phytol in crude extract)	Antibacterial, Antioxidant, Anti-cancer	Amides, Alcohols, Phenols, Phosphorus	(55)
2	*Najas minor*	Ethyl acetate extracts	Phenol, flavonoids,	Antibacterial, Antioxidant	Hexahydrofarnesyl acetone	(56)

			tannins			
3	*Ferula halophila*	Acetone, chloroform,methanol	Acetone extract-phenolic, Flavonoid Chloroform-cholinesterases, cinnamic acid derivatives Methanol extract-tyrosinase, glu11cosidase	`		(57)
4	*Enhalus acoroides*	Methanol extract, leave	Alkaloid, Phenolic, Tannin, Saponins, Flavonoid, Monoterpenes, Sesquiterpenes	Antibacterial, Antioxidant	Hydroxyl groups, Alkanes, Secondary amines, Benzenoid compounds, Phenols	(58)
5	*Vallisneria Americana*	Ethanol extract leave	Alkaloid, terpenoid, phenol	Antidermatitis/ Antifungal	_	(59)
6	*Blyxa echinosperma*	Leaf	Phenolic	Antidermatitis/ Antifungal	Amines	(60)

Molecular Approach towards Increasing the Therapeutic Values

Combining eukaryotic gene expression and molecular technique is a great approach to changing the pattern of developmental stages in plants. The epigenetic processes, such as DNA methylation and demethylation, affect gene expression patterns in plant response to various environmental circumstances that affect development (61). An investigation was carried out on cu-induced protein profiling and methylation of DNA in Hydrilla. Exposure to copper changes the gene expression pattern by rearranging the methyl-transferase domain, chromo-methylase domain, and histone-specific (H3 lysine-9). Copper-induced alterations in DNA methylation were connected to ROS formation, as NADPH oxidase inhibitors lowered the quantity of 8-hydroxy-2′-deoxyguanosine and caused remethylation of demethylated genomic locations (62). Matrix Metalloprotein Proteins (MMPs) are essential in suppressing and invading breast cancer cells through metastasis and angiogenesis mechanisms. The volatile active compounds of *Hydrilla* play a significant role against breast cancer. It is investigated by molecular docking with ligands such as phytol, methylpentadecanoic acid, benzene dicarboxylic acid butyl octyl ester, octadecenoic acid, ergosterol, and dimethyle esitate identified in *Hydrilla verticillata* on MMP-2 and MMP-9. The result showed that ergosterol and dimethyl esitate had binding energy -8.6 and -8.7 KCal/mol towards MMP-2 and MMP-9 receptors, respectively. The natural ligand's binding affinity is -8.0 to -7.8 kcal/mol. Ergost-5-en-3-ol, 22,23-dimethyl-acetate has a higher binding affinity than the native ligand. So, drug-likeness analysis with a bioavailability score of 0.55 indicates these chemicals have anti-cancer properties (63).

Key Insights into *Hydrilla verticillata* and Its Applications

Antitumor Activity

Hydrilla is a submerged plant used medicinally to treat gastrointestinal disorders, boost blood circulation, assist in detoxification, and promote heart and brain health (64). It slows down the process of aging, supports regulation of blood sugar levels, strengthens immunity to safeguard the body against outside threats, and extends endurance (65). Otteliones A and B, found in Hydrilla, are structurally unique, physiologically relevant natural compounds with potent anticancer properties (66).

Antimicrobial Activity

The ethanolic extract of *Hydrilla verticillata* revealed a negative effect against fungus and an excellent inhibitory effect against bacteria. Compared to gram-positive bacteria, gram-negative bacteria are less susceptible to antibiotic activity. However, it doesn't work as an antifungal, as the concentration of the plant's ethanolic extract increases, so does the zone of inhibition for all bacterial strains. Plant extract concentrations of 250 and 500 µg/mL did not prevent *E. Coli* growth, while 750 and 1050 µg/mL resulted in a 9 and 11 mm clearance zone, respectively (39).

Antioxidant Activity

The antioxidant activity of *H. verticillata* is demonstrated in 2006. This experiment involved a thorough extraction of plant components. The extracts were tested for antioxidant activities using non-enzymatic haemoglycosylation and DPPH free radical scavenging activity techniques. The chloroform extract exhibited the maximum antioxidant activity, while the petroleum ether extract had the lowest (64).

CNS Activity

It was found out that *H. verticillata* plant extract improved sleep in rats. The study found that aqueous extracts of *H. verticillata* (AEHV) had a dose-dependent effect on mice's sleeping time after being induced by standard hypnotics such as "pentobarbitone sodium, diazepam, and meprobamate" (64).

Analgesic Activity

To prove that AEHV causes analgesia in mice, two approaches were used: acetic acid-induced writhing and Eddy's hot plate method. In one method, the aqueous extract reduced writhing compared to acetyl-salicylic acid, paracetamol, and morphine. The plant extract increased the analgesic effects of morphine and pethidine (64).

Anticonvulsant Activity

Strychnine and leptazol both cause tonic convulsions with clonus in mice. AEHV delivery resulted in increased average survival time and lower percentage mortality at varied dosages. The aqueous plant extract showed anticonvulsant effects in a dose-dependent manner. However, mixing strychnine or leptazol with Hydrilla extract did not significantly reduce convulsions (64).

Other Uses

This plant weed has anticancer and antibacterial effects and is used to improve GI activity, blood flow, and glucose levels in the blood. It detoxifies and decalcifies the pineal gland and can alleviate stress. It soothes the sympathetic nervous system and stimulates muscular contraction in cells. This plant enhances immunity and nutrition, resulting in healthier skin and hair (64).

Phytol: Wonder Compound of Hydrilla

The aquatic weed *Hydrilla verticillata* has a lot of phytol, a natural linear diterpene fatty alcohol essential to chlorophyll. It has been widely used as a precursor for producing synthetic forms of vitamins E and K. Their commercial applications include cosmetics, shampoos, toilet soaps, household cleansers, and detergents (67, 68). The component phytol plays a vital role in converting this noxious weed into a helpful one. Phytol can be used directly as fatty alcohols without additional conversion. Furthermore, it is a long-chain primary alcohol with strong hydrophobicity, making it useful as a surfactant. "Lauryl alcohol ethoxylate" is primarily utilized as a non-ionic surfactant. However, a product with fewer or no risk factors is required because of the accompanying risks, such as skin irritation, mucous membrane inflammation, and toxicity to aquatic creatures. As phytol is a low-risk chemical, it may be effective for the abovementioned purposes. Because it comes from a natural source, it is renewable, safe, and widely available. Furthermore, natural sources are more stable than synthetic ones (55). A molecular docking study concluded that phytol, a natural phytanic acid, has been shown to activate enzymes in the body that positively impact insulin levels. It can control type 2 diabetes by activating the nuclear receptor and hetero-dimerization of RXR and PPARy by phytanic acid (69). Phytol and its derivatives have been proven to play significant medicinal roles in humans and other animals. It has also been shown to reduce cholesterol concentrations. Phytol-treated mice maintained consistent cholesterol levels 55. The phytol inhibits β-hydroxy β-methylglutaryl-CoA reductase enzyme, lowering cholesterol levels and promoting weight loss (70). Phytol, a branched-chain fatty alcohol derived from chlorophyll, is produced in the gut of ruminant animals by fermentation of plant materials ingested. Phytol can be obtained either synthetically or spontaneously from many sources. *H. verticillata's* ethanolic extract has been reported to inhibit lipase activity, thus offering an intriguing therapy for obesity. Hydrilla extract inhibits lipase most effectively at 125µg/mL due to its substantial amount of flavonoids, terpenoids, and alkaloids (71). One of the studies on anti-inflammatory and immunomodulatory activities and in silico evaluation of potential selective "COX-2 and TNF-α inhibitors" from methanolic extract of *H. verticillata* (L.f.) Royle was found out. For this study, "lipopolysaccharide (LPS)-stimulated RAW 264.7" macrophage cells have been explored. For in silico study, investigation for the underlying

molecular mechanism of the anti-inflammatory activity of plant extract has been carried out by molecular docking and molecular dynamics simulation approaches with COX-2 and TNF-α inhibitors ability against the most potent phytocompound phytol from the plant extract. To evaluate whether the extract causes any toxicity, the cytotoxicity test has been carried out with the Human embryonic kidney cell line (Hek-293), Mouse fibroblast (L929), human mesenchyme stem cells (hMSCs), and human breast epithelial cell line (MCF-10a). Ultimately, our findings suggest that the plant extract has great potential to reduce inflammation without causing any toxicity to normal cells (20). Phytol the compound that makes Hydrilla a wonder of nature, have many therapeutic uses. To ensure safety, efficacy and quality the legal frameworks governing the development and commercialization of plant-based antimicrobials are essential. Regulatory approval typically involves preclinical and clinical evaluations mandated by agencies such as the FDA or EMA to establish the safety and antimicrobial efficacy of these products. Standardization and quality control measures are crucial to guarantee consistent active ingredient levels and stability. Intellectual property (IP) rights play a significant role, allowing developers to patent unique formulations while adhering to benefit-sharing agreements under protocols like Nagoya to respect traditional knowledge.

Challenges and Future Directions

Among 120 species, only eight have been explored for their medicinal properties. In this review study, Hydrilla is the most experimented plant in this family. Hydrilla is the species where all the study aspects have been carried out to explore more about the plant. It has a peculiar character but is highly enriched with vitamins, minerals, and great medicinal properties. Interestingly, it shows ideal results as immunomodulatory and anti-cancer properties also proven by molecular docking procedure. This plant, having phytol as a volatile substance, is responsible for anti-cancer and immunomodulatory properties. But above all, this plant also a rich source of calcium in the earth. So, this can be a future cutting-edge research proposal to identify the pathway to maintain that amount of calcium inside it and different procedures to extract the calcium from this species and utilize it in various products, such as the pharmaceuticals and pharmacological industry. Secondly, this plant has a unique vitamin source, which is a super food. The presence of multiple compounds, like phytol and hexadecanoic acid, their derivatives, can be used to treat various diseases. So, more research work is required in the field of drug discovery, design, and development.

Conclusion

Secondary metabolites produced by bioactive plants could potentially be exploited to create new, synthetic antibacterial agents that are more effective and substances with novel pharmaceutical characteristics via recurrent structural modification. Several possess antiviral, antifungal, and antibacterial qualities, making them an intriguing source of antimicrobial discoveries. The structurally modified natural compounds should show enhanced potency, selectivity, duration of action, and bioavailability at lower toxicity. Pharmaceuticals derived from these plants are affordable, convenient, and devoid of adverse side effects. Numerous phytochemicals have been derived from them since ancient times. Medicines produced from plants have become widely accepted as a source of therapeutic compounds. The value and demand for traditional medicine made from plants is steadily increasing as an approach to curing illnesses. However, research has been done on the medicinal uses of several aquatic macrophytes among different tribes. To ensure that it is beneficial in the future for the discovery of novel drugs and the treatment of various deadly diseases, extensive screening, surveys, and experimental studies must be conducted to verify the tribal applications.

Abbreviations

AMR: Antimicrobial Resistance, MDR: Multidrug resistance, Eos: Essential oils, NPs: Nanoparticles, ROS: Reactive oxygen species, MMPs: Matrix Metalloprotein Proteins.

Acknowledgment

We thank the President and Vice-chancellor of Centurion University of Technology and Management for their constant support and motivation for the research and publications.

Author Contributions

Adarsh Kumar Jain: Writing - original draft. Madhusmita Barik: Review & editing. Bhagyeswari Behera: Conceptualization, Investigation, Writing – original draft, Writing – review & editing.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Ethics Approval

Not applicable.

Funding

None.

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