Review Article

Antibacterial and Antifungal Activities of Water Hyacinth (Eichhornia crassipes) Against Fish Pathogens: A Comprehensive Review of Aquaculture Applications

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ABSTRACT

The rapid expansion of aquaculture has been accompanied by an increasing prevalence of infectious diseases caused by bacterial and fungal pathogens, which continue to constrain global fish production. Conventional disease management strategies rely heavily on antibiotics and synthetic chemotherapeutics; however, the emergence of antimicrobial resistance (AMR), environmental contamination, and regulatory restrictions on antibiotic use have stimulated interest in sustainable, plant-based alternatives. Among the aquatic plants investigated, water hyacinth (*Eichhornia crassipes*), an invasive aquatic macrophyte, has gained considerable scientific attention owing to its rich phytochemical composition and diverse biological activities. The plant contains an array of secondary metabolites, including phenolic compounds, flavonoids, alkaloids, tannins, saponins, and terpenoids, many of which exhibit documented antimicrobial properties. This review critically examines the published literature on the antibacterial and antifungal activities of *E. crassipes* against microorganisms relevant to aquaculture, with particular emphasis on fish-pathogenic species. The review addresses the phytochemical profile of water hyacinth, extraction methods, the mechanisms underlying antimicrobial activity, and evidence from both in vitro and in vivo studies. Furthermore, the potential application of water hyacinth-derived bioactive compounds as eco-friendly alternatives for disease management in cultured fish species is evaluated. Although existing findings indicate promising antimicrobial potential, significant knowledge gaps persist regarding active compound identification, standardization of extraction procedures, toxicity profiling, and large-scale field validation. Future research integrating phytochemical characterization, molecular approaches, and aquaculture-based challenge studies is anticipated to facilitate the development of *E. crassipes*-derived therapeutics for sustainable fish health management.

***Key words*:** Eichhornia crassipes, antibacterial activity, antifungal activity, antimicrobial resistance, medicinal plants, sustainable disease management, aquaculture.

Aquaculture has emerged as one of the most rapidly expanding food-producing sectors globally, contributing substantially to food security, nutritional sustainability, and economic development. The escalating demand for fish and fishery products, combined with the progressive decline of wild fish stocks, has accelerated the intensification of aquaculture practices in both freshwater and marine environments. Despite remarkable technological advances in production systems, disease outbreaks remain a major impediment to sustainable aquaculture development. Pathogenic microorganisms, particularly bacteria and fungi, are responsible for significant reductions in fish productivity through elevated mortality, impaired growth, diminished feed efficiency, and increased treatment expenditure [1, 2].

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Among the disease-causing agents affecting cultured fish, bacterial pathogens account for a substantial proportion of reported outbreaks. Species belonging to the genera Aeromonas, Vibrio, Edwardsiella, Pseudomonas, Flavobacterium, and Streptococcus are frequently implicated in severe infections in freshwater and marine fish species. These pathogens induce a broad range of clinical manifestations, including hemorrhagic septicemia, ulcerative lesions, fin erosion, gill necrosis, and systemic infections, often resulting in high mortality under intensive farming conditions. In addition, fungal-like pathogens such as Saprolegnia spp., Achlya spp., and Aphanomyces spp. represent important challenges in aquaculture, particularly during the egg, larval, and juvenile stages of development.

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The persistence and spread of these pathogens are frequently exacerbated by environmental stressors, suboptimal water quality, overcrowding, and handling-associated stress [2-4].

For several decades, antibiotics and synthetic chemotherapeutic agents have been extensively employed for the prevention and control of microbial infections in aquaculture systems. Although these agents have contributed significantly to disease management, their prolonged and indiscriminate use has generated serious concerns regarding AMR, environmental contamination, and the accumulation of chemical residues in aquatic organisms and surrounding ecosystems. The emergence of antibiotic-resistant bacterial strains has diminished treatment efficacy and has become a global public health concern owing to the potential horizontal transfer of resistance determinants between aquatic and terrestrial environments [5-8]. Natural products derived from plants have attracted considerable scientific attention as potential alternatives to synthetic antimicrobials. These compounds possess broad-spectrum biological activities, including antibacterial, antifungal, antioxidant, anti-inflammatory, and immunostimulatory properties. Bioactive secondary metabolites such as phenolics, flavonoids, alkaloids, tannins, saponins, and terpenoids may interfere with microbial cell membranes, inhibit essential metabolic pathways, suppress virulence factors, and augment host immune responses [9-11].

Among aquatic plants with medicinal potential, water hyacinth (Eichhornia crassipes [Mart.] Solms) has received growing scientific attention. Originally native to the Amazon Basin, this species is currently recognized as one of the world's most problematic invasive aquatic macrophytes, colonizing freshwater ecosystems across tropical and subtropical regions. Despite its well-documented ecological and economic impacts, accumulating evidence indicates that the plant is a rich source of biologically active compounds. Phytochemical investigations have revealed the presence of flavonoids, phenolic acids, alkaloids, tannins, steroids, glycosides, and terpenoid derivatives, many of which exhibit demonstrable antimicrobial properties [12-14].

Despite growing interest in the antimicrobial properties of E. crassipes, available information concerning its application against fish pathogens remains fragmented. Published studies vary considerably in extraction methodology, phytochemical composition, target microorganisms, and experimental design, making it difficult to synthesize a comprehensive understanding of its efficacy and practical relevance in aquaculture. Mechanisms underlying antibacterial and antifungal activities, as well as prospects for large-scale application in fish health management, remain insufficiently elucidated.

The present review, therefore, critically examines the available literature on the antibacterial and antifungal activities of Eichhornia crassipes, with particular emphasis on pathogens relevant to aquaculture. The review summarizes current knowledge on phytochemical composition, evaluates evidence of antimicrobial activity against bacterial and fungal fish pathogens, discusses proposed mechanisms of action, and identifies future research directions required to facilitate the development of water hyacinth-based therapeutics for sustainable aquaculture disease management.

2. BOTANICAL DESCRIPTION, DISTRIBUTION, AND PHYTOCHEMISTRY

2.1 Botanical Description and Geographical Distribution

Eichhornia crassipes (Mart.) Solms, commonly known as water hyacinth, is a free-floating perennial aquatic macrophyte belonging to the family Pontederiaceae [12, 15]. Originating in the Amazon Basin of South America, the species has subsequently spread throughout tropical and subtropical regions worldwide owing to its ornamental value, rapid vegetative propagation, and exceptional ecological adaptability [16, 17]. The plant is characterized by glossy, rosette-arranged leaves, inflated bulbous petioles that confer buoyancy, and an extensive fibrous root system capable of efficient nutrient absorption [18]. Attractive violet to lavender flowers borne on erect spikes have contributed to its widespread introduction into ornamental water bodies [16].

The reproductive success of E. crassipes is attributable to both sexual and asexual propagation. Vegetative reproduction through stolon formation enables rapid population expansion under favorable environmental conditions; dense populations can double their biomass within a few weeks, facilitating extensive colonization of ponds, lakes, reservoirs, irrigation canals, wetlands, and slow-flowing rivers [17]. This extraordinary proliferative capacity has led to the designation of water hyacinth as one of the world's most invasive aquatic plant species [14].

Large-scale infestations of E. crassipes are associated with numerous ecological and socioeconomic consequences. Dense floating mats reduce light penetration, suppress submerged vegetation, alter dissolved oxygen dynamics, impair aquatic biodiversity, obstruct navigation, and interfere with irrigation infrastructure [19, 20]. The impact on fisheries is particularly significant because dense vegetation can alter fish habitats, reduce water quality, and ultimately compromise fish production and ecosystem integrity [20]. However, increasing attention has been directed toward beneficial applications of water hyacinth, including wastewater treatment, phytoremediation, bioenergy production, composting, animal feed supplementation, and pharmaceutical applications [18, 20, 21].

2.2 Phytochemical Composition

The scientific interest in Eichhornia crassipes as an antimicrobial resource is largely attributable to its diverse phytochemical profile. Qualitative and quantitative investigations have demonstrated that different plant organs, including leaves, petioles, roots, and flowers, contain a broad spectrum of secondary metabolites with recognized biological activities [22]. These include phenolic compounds, flavonoids, alkaloids, tannins, saponins, terpenoids, steroids, glycosides, reducing sugars, and antioxidant constituents [13, 23]. The concurrence of these compound classes has attracted considerable attention because many possess antibacterial, antifungal, antioxidant, anti-inflammatory, and cytoprotective properties [24]. Phenolic compounds are considered among the most important contributors to antimicrobial activity in E. crassipes. These metabolites function as defensive molecules in plants and have been reported to inhibit microbial growth through disruption of cell membrane integrity, denaturation of cellular proteins, inhibition of extracellular enzymes, and interference with nucleic acid synthesis [25,26]. Studies examining water hyacinth extracts have consistently detected appreciable concentrations of total phenolics, suggesting that these compounds contribute substantially to the observed antimicrobial effects [13,22].

Flavonoids represent another major class of bioactive constituents in E. crassipes. These polyphenolic compounds can inhibit microbial growth by disrupting cell wall integrity, altering membrane permeability, inhibiting nucleic acid synthesis, and suppressing energy metabolism [27, 28]. Their occurrence in water hyacinth has been confirmed by several phytochemical screening studies, which further suggest that flavonoids may act synergistically with other metabolites to enhance overall antimicrobial efficacy [13,29]. Alkaloids constitute an important component of the phytochemical arsenal of E. crassipes. These nitrogen-containing secondary metabolites exhibit broad-spectrum antimicrobial activity against both Gram-positive and Gram-negative bacteria through interactions with DNA, RNA, and essential enzymes involved in cellular metabolism, thereby inhibiting microbial growth and replication [30, 31]. The presence of alkaloids in water hyacinth extracts has been documented in both aqueous and organic solvent preparations, indicating their widespread distribution within plant tissues [22].

Tannins and saponins further contribute to the biological activity of water hyacinth. Tannins are polyphenolic compounds capable of forming complexes with proteins and polysaccharides, thereby disrupting microbial adhesion, enzyme function, and nutrient acquisition [32]. Saponins possess amphiphilic properties that facilitate interaction with biological membranes, increasing membrane permeability and promoting cellular leakage [33]. The simultaneous occurrence of these compound classes in E. crassipes may therefore enhance overall antimicrobial potential through complementary mechanisms [29].

Terpenoids and steroidal compounds identified in water hyacinth are increasingly recognized for their pharmacological significance. Terpenoids represent one of the largest classes of plant secondary metabolites and have been reported to exhibit antibacterial, antifungal, antiviral, and anti-inflammatory activities [34]. Advances in analytical chemistry, including high-performance liquid chromatography (HPLC), gas chromatography–mass spectrometry (GC–MS), and liquid chromatography–mass spectrometry (LC–MS), have enabled the identification of numerous phenolic acids, flavonoids, fatty acids, sterols, and other biologically active molecules in E. crassipes [13, 23]. GC–MS analyses have revealed compounds such as phytol, hexadecanoic acid derivatives, linolenic acid derivatives, and various aromatic constituents previously associated with antimicrobial and antioxidant activities in medicinal plants [23].

Collectively, synergistic interactions among these phytochemical groups are believed to play a crucial role in determining the antimicrobial efficacy of water hyacinth extracts. Combinations of phenolics, flavonoids, alkaloids, tannins, and terpenoids can simultaneously target multiple cellular pathways, thereby enhancing pathogen inhibition and reducing the likelihood of resistance development [35]. The broad phytochemical diversity of E. crassipes, therefore provides a strong biochemical rationale for its reported antibacterial and antifungal activities.

2.3 Factors Influencing Phytochemical Variability

The phytochemical composition of Eichhornia crassipes is not invariant and can differ considerably according to environmental, physiological, and methodological factors. Secondary metabolite biosynthesis in plants is highly responsive to external conditions, and aquatic macrophytes are particularly sensitive to fluctuations in their surrounding environment. Consequently, variations in the concentration and composition of bioactive compounds may significantly affect the antimicrobial efficacy of extracts obtained from plants harvested in different geographical regions or under differing experimental conditions.

Environmental parameters, including temperature, light intensity, nutrient availability, pH, dissolved oxygen concentration, and water chemistry, have been reported to influence secondary metabolite biosynthesis in aquatic plants [20]. Physiological stress responses, such as those induced by elevated ultraviolet radiation, nutrient limitation, or oxidative stress, are known to enhance the accumulation of phenolic antioxidants and other defensive compounds in several aquatic and terrestrial plant species [36]. Geographical location further contributes to phytochemical diversity, as water hyacinth populations inhabiting distinct climatic zones are exposed to divergent environmental pressures that may alter secondary metabolite profiles [17, 20].Seasonal variation, plant age, and organ type are additional determinants of phytochemical content. Different plant organs accumulate distinct classes of secondary metabolites depending on their physiological roles and exposure to environmental stressors [24]. In E. crassipes, roots, leaves, petioles, and flowers have been reported to contain bioactive compounds at varying concentrations [22, 29]. Root tissues are of particular interest because continuous interaction with aquatic microorganisms and dissolved contaminants may stimulate the production of specialized defensive metabolites. Extraction methodology constitutes a major source of variability in phytochemical studies. Phytochemical recovery depends on solvent polarity, extraction temperature and duration, plant-to-solvent ratio, and sample preparation procedures [37]. Post-harvest processing, including drying method, storage duration, and exposure to heat or light, can further alter the stability of sensitive bioactive compounds [37, 38]. Numerous investigations have reported stronger antimicrobial activity in methanolic and ethanolic extracts of E. crassipes compared with aqueous preparations, suggesting that many biologically active constituents possess moderate polarity [13, 23]. Recent advances in analytical technologies underscore the complexity of phytochemical variation, emphasizing the need for standardized extraction and analytical protocols to facilitate reliable comparisons among studies.

3. MAJOR FISH PATHOGENS IN AQUACULTURE

The rapid intensification of aquaculture has been accompanied by an increased incidence of infectious diseases caused by bacterial, fungal, viral, and parasitic pathogens. Bacterial and fungal diseases in particular impose substantial economic burdens through reduced growth performance, elevated mortality rates, increased treatment expenditures, and trade restrictions [1, 3]. Disease outbreaks are frequently exacerbated by intensive farming practices, environmental stress, poor water quality, overcrowding, and fluctuations in temperature and dissolved oxygen [4]. An understanding of major fish pathogens is therefore essential for evaluating the potential application of plant-derived antimicrobial agents such as E. crassipes.

3.1 Bacterial Fish Pathogens

Aeromonas species

Members of the genus Aeromonas, particularly Aeromonas hydrophila, are among the most significant bacterial pathogens affecting freshwater fish culture worldwide [1]. A. hydrophila is the principal causative agent of motile aeromonad septicemia (MAS), a disease characterized by cutaneous hemorrhages, ulcerations, fin rot, abdominal distension, and systemic septicemia [39]. The pathogen infects a broad range of cultured species, including carp, tilapia, catfish, and ornamental fish, often precipitating severe mortality under stressful conditions [2]. Recent investigations have documented increasing AMR among Aeromonas isolates recovered from aquaculture systems, further emphasizing the need for alternative antimicrobial strategies [40].

Edwardsiella tarda

Edwardsiella tarda is a Gram-negative enteric bacterium responsible for edwardsiellosis, a disease affecting numerous freshwater and marine fish species [41]. Clinical manifestations include skin lesions, internal abscesses, hemorrhages, and septicemia. The intracellular survival capacity and virulence-associated factors of E. tarda often complicate management using conventional antibiotics [42].

Vibrio species

Species of the genus Vibrio, including V. harveyi, V. anguillarum, and V. vulnificus, are among the most significant bacterial pathogens in marine and brackish-water aquaculture, collectively causing vibriosis characterized by hemorrhagic septicemia, tissue necrosis, fin erosion, and high mortality [1, 7]. The emergence of antibiotic-resistant Vibrio strains has further complicated disease management in marine aquaculture systems.

Pseudomonas fluorescens

Pseudomonas fluorescens is an opportunistic pathogen frequently isolated from diseased freshwater fish. The bacterium is associated with fin rot, ulcerative lesions, and systemic infections in fish exposed to environmental stress [3]. Increasing resistance to commonly used antibiotics among Pseudomonas isolates underscores the need for novel antimicrobial alternatives [8].

Flavobacterium columnare

Flavobacterium columnare is the etiological agent of columnaris disease, one of the most destructive bacterial diseases in freshwater aquaculture [43]. Clinical signs include skin erosions, gill necrosis, fin degradation, and respiratory distress. Outbreaks are particularly severe in warm-water species such as tilapia and catfish, where mortality can escalate *rapidly under intensive production conditions.*

Streptococcus species

Streptococcosis caused by Streptococcus agalactiae and Streptococcus iniae has emerged as a major bacterial disease in global aquaculture [44]. Infected fish frequently display exophthalmia, abnormal swimming behavior, meningoencephalitis, and septicemia. The disease is particularly problematic in intensive tilapia farming, where outbreaks can cause substantial economic losses.

3.2 Fungal Fish Pathogens

Saprolegnia species

Members of the genus Saprolegnia are among the most important fungal-like pathogens affecting freshwater fish and fish eggs [45]. Saprolegniasis manifests as cotton-like mycelial growth on the skin, fins, and eggs of infected fish. The disease frequently follows physical injury, environmental stress, or secondary infections and can result in substantial mortality during hatchery operations.

Aphanomyces invadans

Aphanomyces invadans is the causative agent of epizootic ulcerative syndrome (EUS), a devastating disease reported across numerous freshwater and estuarine fish species throughout Asia, Australia, and Africa [46]. The pathogen invades deep muscle tissue, producing severe ulcerative lesions and extensive necrosis, and remains one of the most economically significant fungal-like diseases in tropical aquaculture.

Achlya species

Species of Achlya are opportunistic water molds capable of infecting fish eggs, larvae, and immunocompromised fish, particularly under suboptimal environmental conditions [3]. Although generally less virulent than Saprolegnia, Achlya infections can contribute to significant production losses in hatchery systems, particularly where poor water quality and elevated organic matter concentrations prevail.

Collectively, these bacterial and fungal pathogens continue to represent major challenges to sustainable aquaculture production. The growing prevalence of AMR and regulatory restrictions on antibiotic use have intensified efforts to identify environmentally acceptable alternatives. Plant-derived bioactive compounds, including those derived from Eichhornia crassipes, represent a promising area of investigation in this context.

4. ANTIBACTERIAL ACTIVITY OF EICHHORNIA CRASSIPES

4.1 Evidence from In Vitro Studies

The antibacterial potential of Eichhornia crassipes has attracted increasing scientific interest in response to the global demand for natural antimicrobial compounds capable of reducing reliance on conventional antibiotics. Numerous investigations have evaluated the antibacterial activity of water hyacinth extracts against a broad spectrum of Gram-positive and Gram-negative bacteria, demonstrating variable degrees of microbial inhibition depending on extraction solvent, plant organ, phytochemical composition, and target microorganism [13]. These studies collectively indicate that E. crassipes contains bioactive constituents capable of exerting significant antibacterial effects under laboratory conditions.

Early antimicrobial screening studies demonstrated that crude extracts prepared from water hyacinth leaves and roots exhibited inhibitory activity against several pathogenic bacteria. Phytochemical analyses by Aboul-Enein et al. [22] revealed that extracts with elevated concentrations of phenolic compounds and flavonoids displayed stronger antibacterial activity than extracts with lower phytochemical content. Comparable findings were reported by Lalitha et al. [29], who observed measurable growth inhibition against both Gram-positive and Gram-negative bacteria following treatment with methanolic and ethanolic extracts of E. crassipes.

Antimicrobial activity is commonly assessed using agar well diffusion, disc diffusion, minimum inhibitory concentration (MIC), and minimum bactericidal concentration (MBC) assays [47]. Several studies have reported that methanolic extracts of E. crassipes generally produce larger inhibition zones than aqueous extracts, suggesting that organic solvents recover a greater proportion of biologically active compounds [13, 23]. The susceptibility of bacterial species to water hyacinth extracts varies considerably according to cell wall architecture; however, significant inhibitory activity has been reported against Gram-negative organisms, including aquaculture-relevant pathogens [29]. GC–MS analyses conducted by Othman et al. [23] identified several compounds with documented antimicrobial properties, including phenolic derivatives, fatty acids, terpenoids, and aromatic constituents. The coexistence of multiple bioactive constituents within a single extract may further amplify antibacterial activity through synergistic interactions [35].

Although the majority of available studies have been conducted under in vitro conditions, the collective evidence indicates that E. crassipes possesses measurable antibacterial activity against a diverse range of pathogenic microorganisms. Significant variability among published investigations, attributable to differences in extraction procedures, assay methodologies, and bacterial strains tested [37], underscores the need for standardized protocols and mechanistic studies to accurately evaluate its relevance to aquaculture disease management.

4.2 Activity Against Fish-Pathogenic Bacteria

The increasing prevalence of bacterial diseases in aquaculture has intensified the search for alternative antimicrobial agents. Although relatively few studies have directly evaluated E. crassipes against fish-specific pathogens, available evidence suggests that the plant contains bioactive compounds capable of inhibiting many species taxonomically and physiologically related to major aquaculture pathogens.

Among bacterial fish pathogens, Aeromonas hydrophila has been the most extensively studied in relation to plant-derived antimicrobials. The pathogen harbors numerous virulence factors, including hemolysins, proteases, enterotoxins, and biofilm-forming capabilities [2,39]. Phenolic-rich extracts have been demonstrated to inhibit A. hydrophila growth by disrupting membrane integrity and interfering with bacterial enzyme systems [9]. Given that E. crassipes contains substantial concentrations of phenolics, flavonoids, tannins, and alkaloids [13], researchers have proposed that water hyacinth extracts may exert similar inhibitory effects against Aeromonas species.

The antimicrobial potential of water hyacinth may also be relevant to the management of Edwardsiella tarda infections. Plant-derived polyphenols and flavonoids have been reported to inhibit enteric Gram-negative bacteria through membrane destabilization and oxidative stress induction [28], mechanisms applicable to E. tarda [41]. Similarly, several phytochemicals identified in E. crassipes, particularly flavonoids and terpenoids, have demonstrated inhibitory activity against Gram-negative bacteria with structural similarities to pathogenic Vibrio species [34], suggesting potential for future anti-vibrio applications.

Pseudomonas fluorescens exhibits considerable physiological adaptability and increasing resistance to commonly used antimicrobial agents [8]. Phenolic compounds and tannins from E. crassipes may offer benefits against Pseudomonas infections by interfering with bacterial adhesion, biofilm formation, and cellular communication pathways [32, 35]. Similarly, flavonoids and phenolic compounds present in water hyacinth may possess inhibitory potential against Flavobacterium columnare [43] and streptococcal pathogens [44] through disruption of cell wall synthesis and impairment of energy metabolism [28].

Despite the growing body of circumstantial evidence, direct evaluations of E. crassipes against fish-pathogenic bacteria remain limited. Systematic investigations employing fish-derived bacterial isolates, standardized extraction procedures, MIC analyses, and in vivo challenge trials are necessary to establish the practical value of water hyacinth-derived compounds as therapeutic agents in aquaculture.

4.3 Influence of Extraction Methodology on Antibacterial Activity

The antibacterial efficacy of Eichhornia crassipes is strongly contingent upon the extraction methodology employed, as different procedures determine the type and concentration of phytochemicals recovered from plant tissues [37]. Variations in solvent polarity, extraction duration, temperature, plant organ selection, and sample preparation can substantially affect phytochemical yield and antimicrobial performance, contributing to considerable differences in reported findings.

Among extraction techniques, solvent extraction using polar organic solvents, particularly methanol and ethanol, remains most widely employed owing to its ability to dissolve a broad range of phenolics, flavonoids, alkaloids, and tannins [38]. Methanolic extracts typically contain higher concentrations of total phenolics and flavonoids than aqueous preparations, resulting in enhanced antibacterial activity against both Gram-positive and Gram-negative bacteria [13]. Ethanolic extraction is also extensively utilized because of its relatively low toxicity, cost-effectiveness, and suitability for pharmaceutical applications [29].

Aqueous extracts generally exhibit reduced antibacterial activity compared with organic solvent preparations, as water primarily recovers highly polar compounds and is less effective at extracting lipophilic phytochemicals [37]. Nevertheless, aqueous preparations remain relevant because they may contain water-soluble phenolics, polysaccharides, and glycosides that contribute to biological activity while minimizing solvent residue concerns. Less commonly employed solvents, including acetone, ethyl acetate, chloroform, and hexane, recover distinct phytochemical classes depending on their polarity [38]. Advanced extraction technologies, including ultrasound-assisted extraction, microwave-assisted extraction, and supercritical fluid extraction, offer advantages in terms of improved efficiency, reduced solvent consumption, and preservation of heat-sensitive compounds [48]. Their application to E. crassipes remains limited and warrants future investigation.

The plant organ selected for extraction, extraction temperature, and duration, and post-harvest processing conditions also substantially influence phytochemical composition and, consequently, antibacterial efficacy [22, 29, 38]. Standardized extraction protocols are therefore essential for facilitating meaningful comparisons among investigations and for advancing the development of water hyacinth-derived antibacterial products for aquaculture applications.

4.4 Proposed Mechanisms of Antibacterial Action

The antibacterial activity of Eichhornia crassipes is attributed to the collective action of multiple phytochemical constituents rather than a single bioactive compound. The simultaneous presence of phenolics, flavonoids, alkaloids, tannins, saponins, and terpenoids can generate synergistic effects that enhance antibacterial efficacy and reduce the likelihood of resistance development compared with single-target synthetic antibiotics [35].

Disruption of bacterial cell membrane integrity is among the most widely described mechanisms. Phenolic compounds and flavonoids interact with membrane proteins and phospholipid bilayers, increasing membrane permeability and promoting leakage of essential intracellular constituents, including ions, proteins, nucleotides, and metabolic intermediates, ultimately impairing bacterial viability [26,28]. In parallel, tannins and phenolics form complexes with extracellular and intracellular enzymes, reducing catalytic efficiency and disrupting essential metabolic pathways [26,32].

Flavonoids can additionally inhibit nucleic acid synthesis by interacting with DNA gyrase and topoisomerase enzymes, interfere with RNA synthesis, and impair protein production, collectively restricting bacterial replication [28]. Alkaloids identified in water hyacinth may intercalate into DNA or interfere with DNA-associated enzymes, disrupting replication and transcription and reducing the expression of virulence-associated genes [31]. Saponins and terpenoids further contribute through direct membrane interactions: saponins associate with membrane lipids, increasing permeability and promoting cellular leakage [33], while terpenoids integrate into lipid bilayers to alter membrane fluidity and disrupt nutrient transport and energy generation [34].

Beyond direct bacterial killing, several phytochemicals in E. crassipes may reduce pathogen virulence through biofilm inhibition and quorum-sensing disruption. Biofilms, structured microbial communities embedded in extracellular polymeric matrices, protect bacteria from environmental stress and antimicrobial agents [49]. Fish pathogens, including A. hydrophila, Vibrio spp., and P. fluorescens, rely on biofilm formation as a virulence strategy [2]. Phenolic compounds and flavonoids have been shown to interfere with biofilm development by disrupting cell adhesion, extracellular polymer production, and quorum-sensing signaling pathways [35, 50]. Oxidative stress induction, through the generation of reactive oxygen species (ROS) within bacterial cells, leading to damage of proteins, lipids, and nucleic acids, has also been proposed as a contributing mechanism [24]. The multifaceted nature of these interactions underscores the broad-spectrum antibacterial potential of E. crassipes and highlights the need for further molecular and mechanistic investigations to characterize the specific compounds responsible under in vivo conditions.

5. ANTIFUNGAL ACTIVITY OF EICHHORNIA CRASSIPES

5.1 Evidence from In Vitro Antifungal Studies

In addition to antibacterial properties, Eichhornia crassipes has demonstrated promising antifungal activity against a variety of fungal microorganisms. The increasing incidence of fungal infections in aquaculture, agriculture, and clinical settings has stimulated interest in plant-derived antifungal compounds as sustainable alternatives to conventional synthetic fungicides [51]. Several investigations have reported inhibitory effects of E. crassipes extracts against fungal pathogens, attributed principally to phenolics, flavonoids, tannins, alkaloids, saponins, and terpenoids [13,29].

Initial antifungal assessments employing agar diffusion assays, poisoned food techniques, and spore germination inhibition tests indicated that methanolic and ethanolic extracts generally exhibit greater antifungal activity than aqueous preparations [37], consistent with patterns observed in antibacterial studies. Fungal genera including Aspergillus, Fusarium, Penicillium, and Candida have been reported to be susceptible to water hyacinth extracts [23], providing evidence of broad-spectrum antifungal potential. GC–MS and chromatographic analyses have further identified bioactive compounds with established antifungal properties, including phenolic acids, flavonoids, fatty acid derivatives, and terpenoid constituents [13, 23].

Considerable variability exists among published studies owing to differences in extraction methods, fungal strains, plant tissues selected, and assay procedures [37]. Standardized investigations are therefore required to accurately determine the antifungal potential of water hyacinth and its suitability for practical disease-management applications.

5.2 Relevance to Fish-Pathogenic Fungi

Fungal and fungal-like infections remain important causes of morbidity and mortality in aquaculture, particularly during egg incubation, larval development, and periods of environmental stress [3]. Members of the genera Saprolegnia, Achlya, and Aphanomyces are among the most economically significant pathogens affecting cultured fish and fish eggs [45], and are capable of causing extensive tissue damage, impaired growth, reduced hatchability, and substantial production losses.

Saprolegnia species are the most frequently encountered in freshwater aquaculture. Saprolegniasis typically follows physical injury, handling stress, poor water quality, or secondary bacterial infection, and can spread rapidly through hatchery systems, significantly reducing hatching success [52]. The withdrawal of several synthetic fungicidal treatments owing to environmental and toxicological concerns has intensified interest in plant-derived alternatives [45]. Although direct studies targeting Saprolegnia with E. crassipes extracts remain limited, the observed susceptibility of related fungal organisms to water hyacinth phenolics, flavonoids, and tannins [29] suggests potential for future antifungal applications. Aphanomyces invadans, the causative agent of EUS, represents another major challenge in tropical aquaculture. Current treatment options remain limited, underscoring the need for novel antifungal strategies [46]. Because E. crassipes contains multiple classes of bioactive compounds capable of inhibiting fungal growth, further investigations targeting Aphanomyces species under both laboratory and field conditions are warranted. Similarly, the broad-spectrum antifungal activity reported for water hyacinth suggests potential utility against Achlya species in hatchery settings [3]. Addressing the significant knowledge gap regarding the susceptibility of fish-pathogenic fungi to E. crassipes-derived metabolites should be a priority for future research.

5.3 Proposed Mechanisms of Antifungal Action

The antifungal activity of Eichhornia crassipes arises from the combined effects of multiple phytochemical constituents acting through diverse cellular mechanisms. Phenolic compounds disrupt fungal membrane integrity and interfere with cell wall biosynthesis, impairing growth and development [36]. Flavonoids inhibit fungal enzymes involved in energy metabolism and nucleic acid synthesis while inducing structural alterations within fungal cells [28]. Tannins exert antifungal effects through protein precipitation and inhibition of extracellular enzymes required for colonization and nutrient acquisition [32], while saponins interact with membrane sterols to increase permeability and promote cellular leakage [33].

Terpenoids identified in water hyacinth extracts may further contribute to antifungal activity by disrupting membrane function and inhibiting spore germination and mycelial growth, which are critical stages in the infection cycles of major fungal pathogens [34]. Oxidative stress induction, through promotion of ROS accumulation within fungal cells, has also been proposed as a contributing mechanism [24]. The simultaneous occurrence of these compound classes suggests that multiple antifungal mechanisms may operate concurrently in E. crassipes extracts. However, the majority of available mechanistic studies have employed non-aquatic fungal species, emphasizing the need for further investigations specifically involving fish-pathogenic organisms.

6. APPLICATIONS IN DIFFERENT FISH SPECIES

6.1 Tilapia (Oreochromis spp.)

Tilapia is among the most widely cultured fish groups globally, with intensive production frequently challenged by bacterial diseases caused by A. hydrophila, S. agalactiae, and F. columnare [43, 44]. Plant-derived antimicrobials have received increasing attention as sustainable alternatives to conventional antibiotics in tilapia culture [11]. The phenolics, flavonoids, tannins, and terpenoids of E. crassipes [13] suggest potential as bioactive compounds for disease prevention and management in tilapia farming. Possible delivery approaches include incorporation of standardized extracts into feed formulations, the application of water-based extracts as prophylactic treatments, and integration into broader health-management programs. Previous investigations using medicinal plant additives in tilapia diets have demonstrated improvements in immune responses and resistance to bacterial infections [9], providing a framework for future evaluations of water hyacinth.

6.2 Common Carp (Cyprinus carpio)

Common carp is an economically important freshwater species susceptible to bacterial diseases, including MAS and columnaris disease [1]. The frequent use of antibiotics in carp culture has raised concerns regarding AMR and environmental contamination [5]. Phenolic-rich plant extracts have previously demonstrated inhibitory activity against Aeromonas species associated with carp diseases [9], and water hyacinth-derived compounds could be explored through feed supplementation, immersion treatments, or topical applications for external infections. Direct in vivo studies in common carp remain an important area for future investigation.

6.3 Rohu (Labeo rohita)

Rohu is one of the principal carp species cultured throughout South Asia and is particularly susceptible to infections caused by Aeromonas spp. and E. tarda under intensive conditions [41]. The use of herbal therapeutics has gained acceptance in the rohu culture owing to their perceived safety, availability, and environmental compatibility [10]. Water hyacinth-derived phytochemicals may offer multiple advantages for rohu production, including broad-spectrum antimicrobial activity, antioxidant properties, and potential immunostimulatory effects. Incorporation of standardized extracts into feed could provide continuous phytochemical exposure while minimizing direct chemical release into culture water. However, dosage optimization, palatability, growth performance effects, and long-term safety require thorough evaluation prior to commercial application.

6.4 Catfish (Clarias spp. and Pangasius spp.)

Catfish farming is frequently challenged by bacterial diseases caused by A. hydrophila, E. tarda, and opportunistic Pseudomonas species [2], leading to ulcerative lesions, septicemia, reduced growth, and substantial mortality. The emergence of antibiotic-resistant isolates in these systems has reinforced interest in plant-based alternatives [8]. Water hyacinth grows abundantly in many regions where catfish culture is practiced, potentially providing a low-cost, locally available source of antimicrobial biomass. Extracts rich in phenolics and flavonoids may be developed as feed additives or water-treatment supplements, while the antioxidant properties of E. crassipes phytochemicals may additionally help mitigate oxidative stress associated with infection and intensive culture conditions [18].

6.5 Ornamental Fish Species

Ornamental fish production is particularly vulnerable to bacterial and fungal diseases owing to high stocking densities, transport stress, and frequent handling [3]. Common pathogens include Aeromonas, Pseudomonas, Vibrio, Saprolegnia, and Achlya species. Water hyacinth-derived extracts could potentially be applied as short-duration immersion treatments or prophylactic agents in ornamental fish systems. However, given the high sensitivity of ornamental species to water quality and chemical exposure, detailed toxicity assessments are essential prerequisites for practical implementation.

6.6 Potential Modes of Application in Aquaculture

The practical application of E. crassipes in aquaculture may involve several delivery strategies: feed supplementation for sustained systemic exposure to bioactive compounds; immersion treatments for external bacterial and fungal infections, particularly during hatchery operations; topical formulations for ulcerative lesions; and integrated disease-management approaches combining plant extracts with probiotics, vaccines, and improved husbandry. Standardization of extraction procedures, identification of active compounds, toxicity evaluation, dosage determination, and commercial-scale validation are critical prerequisites for successful practical application [20, 37]. Future research should prioritize controlled in vivo trials in economically important fish species to establish the efficacy, safety, and economic feasibility of water hyacinth-derived antimicrobial products.

7. CHALLENGES, LIMITATIONS, AND FUTURE PERSPECTIVES

7.1 Limitations of Current Research

Despite growing interest in the antimicrobial potential of Eichhornia crassipes, several limitations continue to restrict its practical application in aquaculture. Chief among these is the relatively small number of studies directly evaluating water hyacinth extracts against fish-pathogenic microorganisms [13, 23]. While numerous investigations have demonstrated antibacterial and antifungal activities against human, agricultural, and environmental pathogens, comparatively few have specifically targeted major aquaculture pathogens such as A. hydrophila, E. tarda, V. harveyi, F. columnare, Saprolegnia spp., and A. invadans. Extrapolation of findings from non-aquatic microorganisms to fish pathogens therefore, warrants caution.

The absence of standardized extraction and experimental protocols represents another significant limitation. Existing studies have employed diverse extraction solvents, plant tissues, and antimicrobial assay methodologies, impeding direct cross-study comparisons [37, 38]. Phytochemical variability attributable to environmental conditions, geographical origin, nutrient availability, seasonality, and plant developmental stage [20] further complicates data interpretation. Without systematic phytochemical characterization, it remains difficult to identify which specific metabolites are responsible for observed biological activities.

A critical knowledge gap exists regarding toxicity and biosafety. Although plant-derived products are often perceived as inherently safe, bioactive compounds may exert adverse effects on fish, non-target aquatic organisms, or surrounding ecosystems at inappropriate concentrations [53]. Information on acute toxicity, chronic exposure effects, tissue accumulation, and environmental safety of E. crassipes-derived antimicrobial products remains limited. Comprehensive toxicological assessments are therefore essential before aquaculture applications can be responsibly recommended. Additionally, the predominance of in vitro studies fails to account for the complex interplay of water quality, pathogen load, host immunity, environmental stress, and microbial interactions that influence treatment efficacy under commercial conditions [11].

7.2 Future Research Directions

Future investigations should prioritize the identification and structural characterization of specific bioactive compounds responsible for the antibacterial and antifungal activities of E. crassipes. Advanced analytical approaches, including LC–MS/MS, metabolomics, nuclear magnetic resonance spectroscopy, and high-resolution mass spectrometry, could facilitate the discovery of novel antimicrobial molecules and elucidate their mechanisms of action [18]. Complementary genomic and transcriptomic analyses of microbial responses to phytochemical exposure would provide valuable mechanistic insights, including effects on virulence genes, quorum-sensing pathways, biofilm formation, and AMR mechanisms [7].

Nanotechnology represents another promising avenue. Plant-based nanoparticle systems can enhance antimicrobial efficacy, improve compound stability, and enable targeted delivery of bioactive molecules [54]. Integration of E. crassipes phytochemicals into nanoparticle formulations may improve bioavailability and therapeutic performance against fish pathogens. Exploration of synergistic combinations with probiotics, immunostimulants, vaccines, or other plant-derived compounds is also warranted, as integrated disease-management approaches have demonstrated efficacy in reducing antibiotic dependence [55].

Most critically, well-designed in vivo challenge trials in economically important fish species are needed. These studies should assess survival rates, pathogen loads, immune responses, growth performance, feed utilization efficiency, and histopathological parameters following administration of water hyacinth-derived products. Such investigations are indispensable for determining whether the antimicrobial activity observed in vitro can be translated into practical disease-control strategies for commercial aquaculture.

7.3 Commercial Prospects and Sustainability

The commercial development of antimicrobial products from Eichhornia crassipes offers several attractive advantages. Water hyacinth is one of the most abundant aquatic weeds globally and is routinely removed from water bodies to mitigate ecological and economic damage [14]. Utilizing this biomass for antimicrobial production would transform an invasive environmental burden into a valuable biological resource, supporting sustainable resource management and circular bioeconomy objectives [21].

The widespread availability of water hyacinth at relatively low cost compared with medicinal plants requiring dedicated cultivation may facilitate the production of affordable antimicrobial products for small-scale and resource-limited aquaculture operations. Moreover, reduced dependence on conventional antibiotics would support global AMR mitigation efforts in aquatic production systems [56]. Integration of water hyacinth-derived products into sustainable aquaculture aligns with global initiatives promoting environmentally responsible food production and ecosystem conservation. Nevertheless, successful commercialization will require standardized extraction protocols, regulatory approval, quality-control frameworks, and large-scale efficacy validation under commercial farming conditions.

CONCLUSION

The increasing prevalence of bacterial and fungal diseases in aquaculture, combined with growing concerns over AMR and environmental contamination associated with conventional chemotherapeutics, has intensified the search for sustainable disease-management strategies. Plant-derived antimicrobial compounds have emerged as promising alternatives for improving fish health while reducing dependence on synthetic antibiotics. Among aquatic plants investigated, Eichhornia crassipes has attracted considerable scientific interest owing to its widespread availability, rich phytochemical composition, and diverse biological activities.

This review demonstrates that E. crassipes contains a broad spectrum of bioactive compounds including phenolics, flavonoids, alkaloids, tannins, saponins, terpenoids, and steroidal constituents that collectively confer significant antibacterial and antifungal properties. Available evidence indicates that water hyacinth extracts inhibit microbial growth through multiple mechanisms: disruption of cell membrane integrity, enzymatic inhibition, interference with nucleic acid synthesis, biofilm suppression, quorum-sensing inhibition, and oxidative stress induction. This multifaceted mode of action may provide advantages over conventional antimicrobials by reducing the probability of rapid resistance development.

Despite encouraging findings, direct evaluations involving major aquaculture pathogens remain limited, and most published studies have focused on general microbial species rather than pathogens isolated from diseased fish. Antimicrobial efficacy is strongly influenced by geographical origin, environmental conditions, plant tissue selection, phytochemical variability, and extraction methodology. Considerable methodological heterogeneity among published investigations emphasizes the need for standardized approaches and robust phytochemical characterization.

From an aquaculture perspective, E. crassipes offers several attractive attributes: it is widely distributed, rapidly renewable, and frequently regarded as an invasive nuisance. Converting this abundant biomass into value-added antimicrobial products could yield concurrent environmental and economic benefits while advancing sustainable aquaculture practices. Potential delivery modes include feed additives, immersion treatments, topical formulations, and integrated health-management programs aimed at minimizing antibiotic usage.

Key challenges requiring resolution prior to commercial adoption include comprehensive toxicity profiling, controlled in vivo challenge trials, dose-optimization studies, pharmacological investigations, and long-term environmental assessments. The isolation and structural characterization of active compounds, alongside mechanistic studies at molecular and cellular levels, will be essential for fully elucidating the therapeutic potential of the plant.

In conclusion, Eichhornia crassipes represents a promising yet underutilized source of natural antibacterial and antifungal compounds with meaningful potential for sustainable aquaculture disease management. Continued multidisciplinary investigation integrating phytochemistry, microbiology, molecular biology, toxicology, and applied aquaculture science will be essential for translating laboratory findings into practical disease-control solutions. Such research may ultimately contribute to the development of environmentally responsible antimicrobial strategies that enhance fish health, reduce antibiotic dependence, and support the long-term sustainability of global aquaculture.

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