

TERMINALIA CHEBULA AS A SUSTAINABLE PHYTOTHERAPEUTIC FOR THE CONTROL OF *AEROMONAS HYDROPHILA* IN *CHANNA STRIATA*: CURRENT EVIDENCE, MECHANISMS, AND RESEARCH GAPS

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ABSTRACT

Aeromonas hydrophila is a major threat to fish health in freshwater aquaculture and is closely associated with economic problems, including motile Aeromonas septicemia, poor growth, and increased mortality in farmed fish. Antibiotic abuse in combating these bacterial infections has also led to considerable concern about the problem of environmental pollution, the development of antimicrobial resistance, and the contamination of aquatic food products. Thus, medicinal plants have been considered as environmentally friendly options for treating diseases in aquaculture. *Terminalia chebula* Retz., also known as Haritaki, has been chosen due to its unique phytochemistry and diverse biological effects. This study evaluates the antibacterial and immunomodulatory properties of *T. chebula*, particularly against *A. hydrophila*, for its potential application in fish breeding in *Channa striata*. In order to investigate phytochemical content, antibacterial mechanisms, the effect on immunological response, and the application of *T. chebula* in sustainable aquaculture, a comprehensive review of scientific literature is conducted. The list of important active compounds includes gallic acid, ellagic acid, chebulagic acid, chebulinic acid, different types of flavonoids, and hydrolyzable tannins. They have antibacterial, antioxidative, anti-inflammatory, and immunomodulating properties. Nowadays, there is information about possible mechanisms of action of these active compounds, which can be related to the inhibition of bacterial growth by disruption of the cell membrane, enzyme inhibition, generation of oxidative stress, inhibition of virulence factors, or biofilm formation. The presence of polyphenols in *T. chebula* can promote an increase of antioxidative defense and innate immune response. However, notable deficiencies still exist in terms of dosing standardization, toxicity assessment, knowledge about the underlying molecular mechanisms, field testing in large numbers, and the effects on other species of fish. All the results obtained confirm that *T. chebula* is a potentially valuable plant treatment for overcoming the problem of antibiotic dependency and achieving sustainable disease management in freshwater aquaculture. In order to create safe and standardized preparations of *T. chebula*, future studies need to combine the above-mentioned disciplines.

Keywords: *Aeromonas hydrophila*, *Channa striata*, *Terminalia chebula*, Antibacterial Activity, Fish Immunity, Antimicrobial Resistance, Sustainable Aquaculture, Medicinal Plants

INTRODUCTION

Aquaculture is crucial for the sustenance of global food security, nutritional sustainability, and economic growth. Being one of the fastest-growing food industries globally, it has seen many developments, especially regarding the adoption of intensive aquaculture methods. Nevertheless, it has also brought about an increase in the prevalence of infectious diseases that affect the health status of fish, lower productivity, and profits (Harikrishnan and Balasundaram, 2005; Abdella *et al.*, 2024). According to Abdella *et al.*, (2024), disease incidence has been found to be among the major factors that pose a threat to sustainable aquaculture practices, resulting in huge economic losses due to higher mortality, poor growth rates, costs of treatment, and market volatility. The diverse pathogens causing diseases in fish raised on farms include

bacteria due to their ubiquitous nature, easy transmission, survival abilities, and resistance to treatments (Semwal *et al.*, 2023) (Zhu, 2020; Reverter *et al.*, 2021).

Given its nutritional value, rapid growth, popularity among consumers, medicinal significance, and adaptability to varied environmental conditions, the Striped murrel fish, *Channa striata*, is a commercially important fish that is extensively cultured in South and Southeast Asian countries (Priyadarshini *et al.*, 2017; Samayanpaulraj *et al.*, 2020). This fish species holds commercial importance in India and many Southeast Asian countries, contributing significantly to aquaculture production in the region. Yet, *C. striata* has become increasingly susceptible to infectious diseases, especially bacterial infections due to *A. hydrophila*, owing to intensification in their culture (Priyadarshini *et al.*, 2017; Samayanpaulraj *et al.*, 2020). Studies report infections of *Aeromonas* resulting in serious ulcers, hemorrhage, reduced feeding activity, poor physiological performance, and mortality in murels under culturing conditions. These findings underscore the pathogen's increasing significance in murrel aquaculture (Samayanpaulraj *et al.*, 2020).

However, the available evidence on the efficacy of using *T. chebula* for the treatment of *A. hydrophila* infection in *C. striata* is still inconclusive, although there has been growing interest in medicinal plant-based treatments. Most of the current literature available mainly focuses on the pathogenicity of *A. hydrophila* or the chemical composition of *T. chebula*, individually. A complete analysis integrating antibacterial properties, immunomodulatory effects, host-pathogen interaction, relevance to aquaculture, and translation of research findings into practice. Additionally, many questions about species-specificity, the molecular mechanism involved, dosing, toxicity, and applicability for commercial purposes have yet to be answered. (Bulbul *et al.*, 2022; Wang *et al.*, 2024)

LITERATURE SEARCH STRATEGY

Relevant literature for this review was collected from Scopus, Web of Science, PubMed, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar. Publications between 2005 and 2025 were screened using keywords related to "*Terminalia chebula*," "*Aeromonas hydrophila*," "*Channa striata*," "aquaculture," "fish immunity," "phytotherapy," "phytobiotics," "antibacterial activity," "medicinal plants," "antimicrobial resistance," and "sustainable aquaculture."

Omission criteria included duplicates, non-English journals, papers with inadequate methodology details, and studies that had little relevance to the goals of the review. While landmark studies were included to put things into perspective, recent studies published within the last decade took precedence due to recent advances in science. In order to assess the current knowledge of *Terminalia chebula*'s antimicrobial action, its immunomodulatory effects, therapeutic uses, drawbacks, and future as a sustainable plant-based treatment for infections by *Aeromonas hydrophila* in fish aquaculture, a critical analysis and synthesis of the reviewed literature were performed.

BIOLOGY, PATHOGENICITY, AND VIRULENCE MECHANISMS OF AEROMONAS HYDROPHILA

Aeromonas hydrophila is an aerotolerant and facultative anaerobic, Gram-negative, rod-shaped bacterium belonging to the Aeromonadaceae family. It is a common constituent of natural microbial populations found in water bodies such as rivers, lakes, ponds, reservoirs, and even aquatic farms (Janda and Abbott, 2010; Rasmussen-Ivey *et al.*, 2016). Even though it is widely prevalent in nature, *A. hydrophila* acts as an opportunistic pathogen and can infect various animals such as fishes, amphibians, reptiles, birds, mammals, and even humans if conditions favor its pathogenicity (Fernández-Bravo and Figueras, 2020). (Semwal *et al.*, 2023)

MAS is a major threat to fish populations worldwide, caused by motile *Aeromonas* septicemia bacteria. The symptoms reported for MAS infections are hemorrhages, ulceration, erosion of fins, distended abdomen, protrusion of eyes, septicaemia, tissue death, loss of appetite, lethargy, and increased mortality (Cipriano *et al.*, 1984; Harikrishnan and Balasundaram, 2005; Austin and Austin, 2016). Environmental factors, which compromise immunity and cause growth of the pathogens, such as poor water conditions,

overcrowding, malnourishment, low levels of dissolved oxygen, and changes in temperature, often trigger infections (Harikrishnan and Balasundaram, 2005; Liu *et al.*, 2020)

The regulation of virulence-associated genes in *A. hydrophila* is further controlled through quorum-sensing mechanisms. Through cell-to-cell communication facilitated by signaling molecules, quorum sensing allows bacterial populations to coordinate collective actions (Rasmussen-Ivey *et al.*, 2016). Toxin synthesis, biofilm formation, motility, stress adaptation, and general pathogenicity are all impacted by this regulatory mechanism. As a result, quorum sensing has become a desirable target for alternative disease-management techniques meant to reduce bacterial pathogenicity without applying the severe selective pressures connected with traditional antibiotics. (Semwal *et al.*, 2023) (Rama Devi *et al.*, 2016)

ANTIBIOTIC RESISTANCE AND LIMITATIONS OF CONVENTIONAL DISEASE MANAGEMENT

Antimicrobial resistance has emerged as a significant challenge to the sustainability of global aquaculture. The constant exposure of bacterial populations to antimicrobial agents creates intense selective pressure, promoting the survival and proliferation of resistant strains (Romero *et al.*, 2012; Stratev and Odeyemi, 2016). As a result, various bacterial pathogens, including *Aeromonas hydrophila*, have developed resistance to commonly used antibiotics, leading to diminished treatment effectiveness and more complex disease management. Numerous studies have revealed that *A. hydrophila* isolates exhibit high resistance to β -lactam antibiotics, particularly ampicillin. Additionally, sporadic instances of resistance to oxytetracycline and sulfonamides have also been documented (Stratev and Odeyemi, 2016; Jeamsripong *et al.*, 2025). In intensive aquaculture systems, the rise of multidrug-resistant bacteria increases the risk of disease outbreaks and complicates therapeutic measures (Abdul Kari *et al.*, 2022).

TERMINALIA CHEBULA: PHYTOCHEMISTRY AND PHARMACOLOGICAL PROPERTIES

For centuries, traditional medical systems such as Ayurveda, Siddha, Tibetan, and Unani have extensively utilized *Terminalia chebula* Retz. (Family: Combretaceae), Commonly known as haritaki or black myrobalan. This medicinal plant is widely distributed across South and Southeast Asia (Naqvi *et al.*, 2010; Kumar *et al.*, 2023). The fruits, in particular, are highly valued for their diverse array of physiologically active phytochemicals, which exhibit antibacterial, antioxidant, anti-inflammatory, hepatoprotective, antiviral, anticancer, and immunomodulatory properties (Naqvi *et al.*, 2010; Tiwana *et al.*, 2024). Owing to this broad pharmacological spectrum, *T. chebula* has attracted increasing scientific interest as a potential natural therapeutic agent for both human and veterinary applications. (Bulbul *et al.*, 2022; Nigam *et al.*, 2020; Wang *et al.*, 2024; Zhang *et al.*, 2019; Cock, 2015) (Xue *et al.*, 2026)

The therapeutic efficacy of *T. chebula* is largely attributed to its rich phytochemical composition. Phytochemical investigations have identified hydrolyzable tannins, phenolic acids, flavonoids, alkaloids, glycosides, terpenoids, anthraquinones, and other secondary metabolites within its fruits (Naqvi *et al.*, 2010; Kumar *et al.*, 2023). Among these, tannins are the most abundant and are considered central to the plant's biological activities. Several studies have noted that the concentration and composition of these bioactive compounds can vary significantly depending on factors such as geographical origin, maturation stage, extraction method, and environmental conditions, which in turn may influence the biological activity of *T. chebula* extracts (Kumar *et al.*, 2023). (Nigam *et al.*, 2020; Wang *et al.*, 2024)

Among the diverse phytochemicals present in *Terminalia chebula*, gallic acid and ellagic acid are considered key phenolic constituents. These compounds exhibit strong antioxidant activity through mechanisms such as free radical scavenging, metal chelation, and prevention of oxidative damage (Tiwana *et al.*, 2024). In addition to their antioxidant properties, gallic acid and ellagic acid have demonstrated antibacterial activity against a wide spectrum of Gram-positive and Gram-negative microorganisms by disrupting cell membranes, inhibiting enzymatic systems, and interfering with bacterial metabolism (Kumar *et al.*, 2023). These dual characteristics are particularly relevant in aquaculture, where bacterial infections and oxidative stress frequently coexist during disease outbreaks. Hydrolyzable tannins, including corilagin,

punicalagin, chebulagic acid, and chebulinic acid, represent another group of extensively studied bioactive components of *T. chebula* (Naqvi *et al.*, 2010; Tiwana *et al.*, 2024). These compounds impede microbial growth through protein precipitation, destabilization of cell membranes, inhibition of enzymatic activity, and suppression of virulence-associated processes. Their potent antibacterial and anti-inflammatory properties have been well documented (Kumar *et al.*, 2023). Importantly, tannins may also interfere with bacterial adhesion and biofilm formation, mechanisms that are critical to the pathogenicity of *Aeromonas hydrophila* and other aquatic pathogens. (Wang *et al.*, 2024) (Manosroi *et al.*, 2010; Yang *et al.*, 2014)

Flavonoids constitute another significant class of phytochemicals in *T. chebula*. These compounds are recognized for their ability to mitigate oxidative stress by reducing reactive oxygen species (ROS) production and preventing oxidative damage to cellular structures (Tiwana *et al.*, 2024). Beyond their antioxidant role, flavonoids are known to modulate immune responses by enhancing phagocytosis, stimulating cytokine release, and regulating inflammatory processes. Consequently, flavonoid-rich extracts of *T. chebula* hold considerable potential as therapeutic agents in aquaculture, offering both disease-preventive and health-promoting benefits for fish populations.

Overall, the existing literature provides substantial evidence supporting the medicinal potential of phytochemicals present in *Terminalia chebula*. The combination of multiple bioactive compounds with diverse biological effects offers the dual advantage of combating bacterial infections while simultaneously enhancing host immunity and maintaining oxidative balance. In light of these properties, elucidating the mechanisms through which *T. chebula* exerts its antibacterial activity against *Aeromonas hydrophila* is crucial for evaluating its applicability in aquaculture disease management. Together, these data highlight the plant's promise as a multifunctional phytotherapeutic agent capable of addressing both pathogen control and host well-being in aquaculture systems.

ANTIBACTERIAL MECHANISMS OF TERMINALIA CHEBULA AGAINST AEROMONAS HYDROPHILA

The antibacterial activity of *Terminalia chebula* is widely attributed to its rich phytochemical composition, which includes high concentrations of hydrolyzable tannins, phenolic acids, flavonoids, and other polyphenols (Naqvi *et al.*, 2010; Rehman *et al.*, 2019; Kumar *et al.*, 2023; Tiwana *et al.*, 2024). Several studies have confirmed the ability of *T. chebula* extracts to inhibit the growth of both Gram-positive and Gram-negative bacteria, including aquatic microorganisms (Bag *et al.*, 2013; Kumar *et al.*, 2023). Unlike conventional antibiotics that typically act through limited biological pathways, the phytochemicals of *T. chebula* are believed to employ multiple complementary mechanisms against bacterial pathogens, thereby reducing the likelihood of resistance development (Dawood *et al.*, 2018; Tiwana *et al.*, 2024). (Bulbul *et al.*, 2022; Wang *et al.*, 2024) (Wang *et al.*, 2025)

Membrane Disruption

One of the major antibacterial mechanisms involves disruption of the structural integrity of bacterial cell membranes. Phenolic compounds such as gallic acid and ellagic acid interact with membrane proteins and phospholipid bilayers, increasing membrane permeability and causing leakage of intracellular contents, ultimately leading to the breakdown of essential physiological processes (Kumar *et al.*, 2023; Tiwana *et al.*, 2024). Membrane destabilization is a well-recognized hallmark of bacterial inhibition by phenolic plant compounds (Cushnie and Lamb, 2011; Borges *et al.*, 2013). This mechanism is particularly relevant for Gram-negative bacteria such as *Aeromonas hydrophila*, whose additional outer membrane layer confers resistance to external stressors.

Enzyme Inhibition by Hydrolyzable Tannins

Another important group of antibacterial compounds is the hydrolyzable tannins, such as chebulagic acid, chebulinic acid, corilagin, and other molecules present in *T. chebula* (Naqvi *et al.*, 2010; Kumar *et al.*, 2023). Tannins can interact with proteins and enzymes through hydrogen bonding and hydrophobic interactions, leading to protein aggregation and enzyme deactivation (Scalbert, 1991; Daglia, 2012). Such interactions impair bacterial metabolism, nutrition, respiration, and growth. Previous studies

have demonstrated that tannins can effectively suppress bacterial enzyme activity, which is a critical factor underlying pathogenicity and virulence (Daglia, 2012; Kumar *et al.*, 2023).

The ability of bacteria to produce biofilms is increasingly recognized as a critical virulence factor of *Aeromonas hydrophila*, enabling survival and resistance to antibacterial agents under adverse environmental conditions (Declercq *et al.*, 2013; Rasmussen-Ivey *et al.*, 2016). Biofilms are defined as microbial communities encased within extracellular polymeric matrices, which protect host defense mechanisms and therapeutic interventions (Declercq *et al.*, 2013). Polyphenolic compounds and tannins derived from medicinal plants have been shown to inhibit bacterial adhesion to surfaces and prevent biofilm formation (Borges *et al.*, 2013; Kumar *et al.*, 2023). Although direct studies on the effects of *Terminalia chebula* against *A. hydrophila* biofilm formation are limited, existing evidence strongly suggests potential efficacy (Rama Devi *et al.*, 2016).

Another suggested antibacterial mechanism of *T. chebula* involves the induction of oxidative stress in microorganisms. While *T. chebula* is widely recognized for its antioxidant activity in animals, certain phenolic compounds can act as pro-oxidants in bacterial cells (Bag *et al.*, 2013; Kumar *et al.*, 2023). Oxidative damage to proteins, nucleic acids, and phospholipids compromises cell integrity and leads to growth inhibition. This oxidative stress is therefore considered an important contributor to the antimicrobial activity of *T. chebula* extracts against diverse microorganisms.

Table 1. Major phytochemicals identified in *Terminalia chebula* and their proposed antibacterial mechanisms against bacterial pathogens. Source: Compiled by the authors from the cited literature.

Phytochemical	Chemical Class	Proposed Antibacterial Mechanism	Potential Effect on <i>A. hydrophila</i>	Reference
Gallic acid	Phenolic acid	Membrane disruption, oxidative stress induction	Increased membrane permeability and growth inhibition	Kumar <i>et al.</i> , (2023); Tiwana <i>et al.</i> , (2024)
Ellagic acid	Polyphenol	Enzyme inhibition and metabolic disruption	Reduced cellular activity and bacterial proliferation	Kumar <i>et al.</i> , (2023)
Chebulagic acid	Hydrolysable tannin	Protein precipitation and anti-virulence activity	Suppression of bacterial growth and pathogenicity	Naqvi <i>et al.</i> , (2010); Kumar <i>et al.</i> , (2023)
Chebulinic acid	Hydrolysable tannin	Membrane destabilization and enzyme inhibition	Impaired bacterial survival	Kumar <i>et al.</i> , (2023)
Corilagin	Tannin	Antioxidant and anti-biofilm activity	Reduced biofilm formation and persistence	Kumar <i>et al.</i> , (2023); Tiwana <i>et al.</i> , (2024)
Flavonoids	Polyphenols	Quorum-sensing interference and oxidative stress modulation	Reduced virulence expression and bacterial adaptation	Borges <i>et al.</i> , (2014); Tiwana <i>et al.</i> , (2024)
Tannins	Polyphenolic compounds	Protein binding and nutrient deprivation	Growth suppression and metabolic inhibition	Scalbert (1991); Daglia (2012)
Mixed phenolic compounds	Secondary metabolites	Synergistic antibacterial action	Multi-target inhibition reducing resistance potential	Rehman <i>et al.</i> , (2019); Tiwana <i>et al.</i> , (2024)

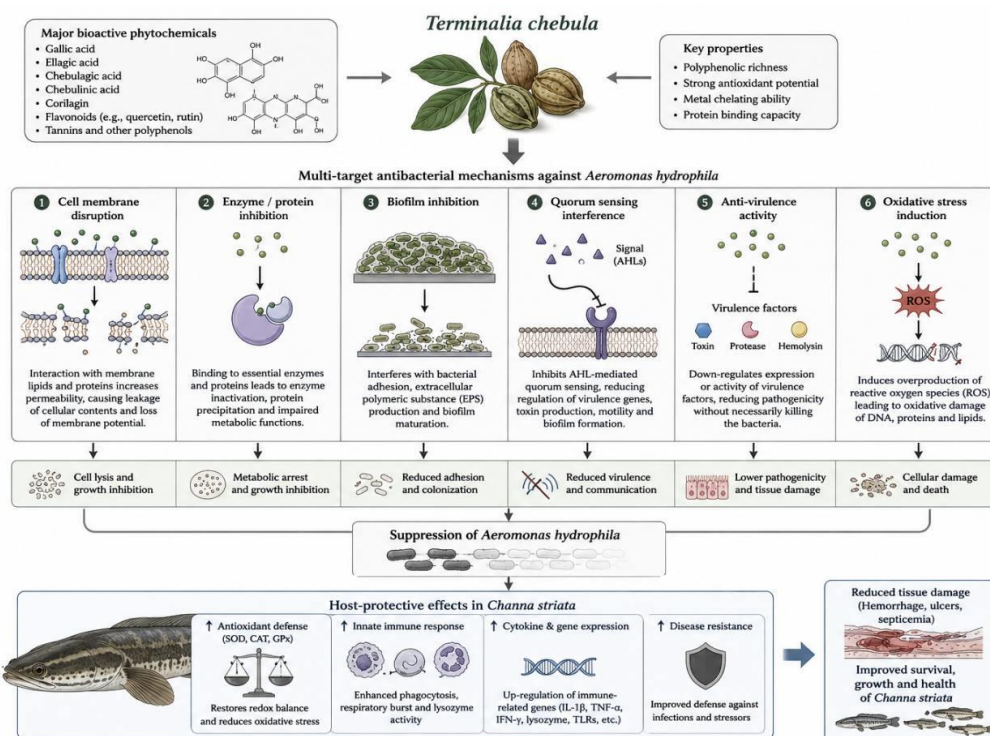


Figure 1. Proposed antibacterial pathways through which phytochemicals of *Terminalia chebula* suppress *Aeromonas hydrophila*. Bioactive compounds may inhibit bacterial growth through membrane disruption, protein precipitation, biofilm inhibition, quorum-sensing interference, and oxidative stress induction, ultimately reducing infection severity and improving fish health. Created by the authors based on information synthesized from the cited literature.

Overall, current findings suggest that *T. chebula* exerts antibacterial activity through multiple interconnected mechanisms, including membrane disruption, protein coagulation, enzyme inhibition, oxidative stress induction, biofilm inhibition, and interference with virulence-associated pathways. The ability to simultaneously target several bacterial functions likely explains the broad antimicrobial spectrum observed in *T. chebula* extracts. However, limited research has specifically examined its effects against *Aeromonas hydrophila* and *Channa striata*. Further in vivo trials are required to validate these mechanisms under practical aquaculture conditions.

The principal phytochemicals of *T. chebula* and their proposed antibacterial mechanisms are summarized in Table 1, while the suggested antibacterial pathways by which *T. chebula* phytochemicals inhibit *A. hydrophila* are illustrated in Figure 1.

IMMUNOMODULATORY AND ANTIOXIDANT EFFECTS OF *TERMINALIA CHEBULA* IN FISH

Among medicinal herbs, *Terminalia chebula* has attracted considerable scientific interest due to its diverse phytochemical profile, including polyphenols, tannins, flavonoids, gallic acid, ellagic acid, chebulagic acid, and chebulinic acid. These compounds have been consistently reported to exhibit both immunomodulatory and antioxidative properties (Saleem *et al.*, 2002; Bag *et al.*, 2013; Kumar *et al.*, 2023). The multifunctional nature of these phytochemicals is particularly important, as they can modulate several physiological pathways simultaneously, including those related to immune response, oxidative balance, and inflammation (Uribe *et al.*, 2011). (Vijayaram *et al.*, 2022; Vallejos-Vidal *et al.*, 2016; Mohan *et al.*, 2023) (Wang *et al.*, 2016; Tang *et al.*, 2014)

In terms of host defense, fish primarily rely on innate immunity as their major line of protection against infectious microorganisms. The key components of the innate immune system include phagocytes,

lysozymes, complement proteins, respiratory burst reactions, and antimicrobial peptides (Magnadóttir, 2006; Uribe *et al.*, 2011). Several studies have reported that plant-derived compounds can enhance these defense mechanisms by stimulating macrophages and leukocytes to proliferate and produce antimicrobial substances (Esteban, 2012; Chakraborty and Hancz, 2011). Notably, gallic acid and its phenolic derivatives present in *Terminalia chebula* have been shown to activate immune cell functions and regulate inflammation pathways (Bag *et al.*, 2013; Rathinamoorthy and Thilagavathi, 2014).

The antioxidative effect of *Terminalia chebula* is among the most extensively studied pharmacological properties of this plant. Laboratory analyses have demonstrated that *T. chebula* extracts possess strong free radical scavenging activity, metal ion chelation capacity, reductive potential, and the ability to inhibit lipid peroxidation (Saleem *et al.*, 2002; Srikumar *et al.*, 2007; Bag *et al.*, 2013). These antioxidant effects are attributed to the plant's phytochemicals, which can effectively neutralize reactive oxygen species (ROS) and protect cellular components from oxidative damage (Rathinamoorthy and Thilagavathi, 2014). Consequently, supplementation with *T. chebula* phytochemicals may help prevent oxidative stress associated with infections and other adverse conditions. (Vijayaram *et al.*, 2022; Al-Niaeem *et al.*, 2026) (Ekambaram *et al.*, 2022)

The evidence summarized above indicates that the beneficial effects of *Terminalia chebula* extend beyond direct antibacterial activity. Several phytochemicals exhibit complementary immunomodulatory and antioxidant properties that may collectively improve fish health, enhance resistance to *Aeromonas hydrophila* infection, and reduce physiological stress. Such multifunctional characteristics support the potential use of *T. chebula* as a sustainable phytotherapeutic agent in aquaculture. The proposed immunomodulatory and antioxidant pathways through which *Terminalia chebula* may enhance disease resistance in fish are illustrated in Figure 2.

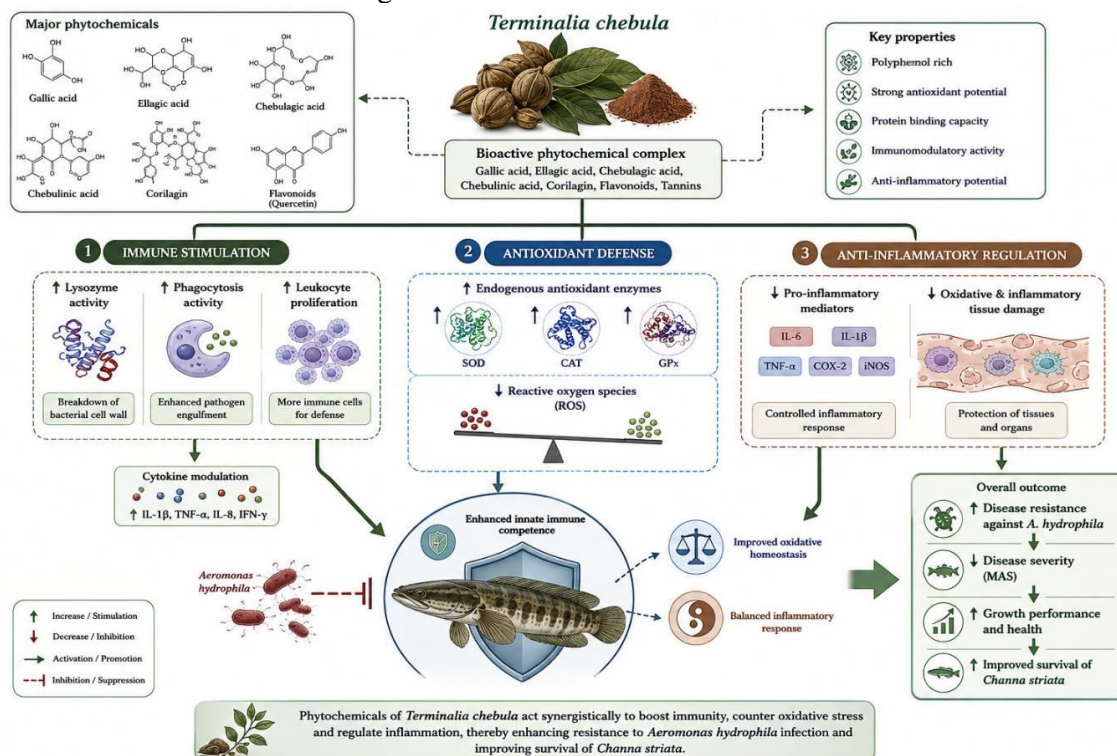


Figure 2. Proposed immunomodulatory and antioxidant mechanisms of *Terminalia chebula* in fish. Bioactive phytochemicals may enhance innate immune responses, stimulate antioxidant enzyme systems, regulate inflammatory processes, and improve resistance against *Aeromonas hydrophila* infection, ultimately promoting survival and health in *Channa striata*. Created by the authors based on information synthesized from the cited literature.

EVIDENCE SUPPORTING THE USE OF *TERMINALIA CHEBULA* AND PLANT-DERIVED THERAPEUTICS AGAINST *AEROMONAS HYDROPHILA* IN FISH

The use of medicinal plants in aquaculture has attracted significant scientific interest over the past two decades due to their effectiveness in improving fish health, inducing immune responses, promoting growth, and reducing mortality caused by bacterial infections (Citarasu, 2010; Galina *et al.*, 2009; Van Hai, 2015). The emergence of antimicrobial resistance, environmental pollution, and antibiotic residues has further necessitated the identification of sustainable measures that enhance fish health while conserving aquatic ecosystems (Austin and Austin, 2016; Awad and Awaad, 2017). In this context, numerous studies have investigated plant-based products for the prevention and treatment of *Aeromonas hydrophila* infections, among other aquatic pathogens (Soltani *et al.*, 2019; Zhu, 2020) (Caipang, 2020).

Additionally, several other medicinal plants such as *Andrographis paniculata*, *Ocimum sanctum*, *Curcuma longa*, *Moringa oleifera*, *Phyllanthus emblica*, and *Zingiber officinale* have shown great potential in terms of their antibacterial and immunomodulating effects in aquaculture species (Citarasu *et al.*, 2006; Chakraborty and Hancz, 2011; Awad and Awaad, 2017; Elumalai *et al.*, 2020). The inclusion of such medicinal plants in fish diets has regularly resulted in better growth performance, higher antioxidant enzyme levels, greater disease resistance, and lower mortality after bacterial infection. These results suggest that medicinal plants can indeed be regarded as versatile feed supplements for aquaculture purposes.

Although no direct studies have yet examined the effects of *Terminalia chebula* against *Aeromonas hydrophila* in *Channa striata*, substantial evidence supports its broad-spectrum antimicrobial activity against diverse pathogenic microorganisms. The pioneering study by Saleem *et al.*, (2002) demonstrated that *T. chebula* exhibited significant antibacterial effects, largely attributed to its hydrolyzable tannins and polyphenols. Subsequent research confirmed its inhibitory activity against multiple bacterial strains, including *Escherichia coli*, *Staphylococcus aureus*, *Salmonella typhi*, *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, and even multidrug-resistant isolates (Bag *et al.*, 2013; Rehman *et al.*, 2019; Kumar *et al.*, 2023). These findings are particularly relevant to aquaculture, as many of the antibacterial mechanisms overlap with those required to combat aquatic pathogens. (Semwal *et al.*, 2023; Abdul Kari *et al.*, 2022) (Harikrishnan and Balasundaram, 2008; Pachanawan *et al.*, 2008)

Recent phytochemical and microbiological studies have highlighted that hydrolyzable tannins such as chebulagic acid, chebulinic acid, and corilagin can interfere with bacterial virulence factors rather than exerting purely bactericidal effects (Tiwana *et al.*, 2024; Kumar *et al.*, 2023). These anti-virulence mechanisms include inhibition of extracellular enzymes, disruption of quorum sensing, prevention of biofilm formation, and modulation of virulence-associated gene expression. Given that *A. hydrophila* relies heavily on these processes for pathogenicity, the anti-virulence activity of *T. chebula* may represent a major advantage over conventional antibiotics.

In addition, several studies have demonstrated that natural plant-based feed additives can enhance fish survival rates under bacterial challenge conditions. Herbal immunostimulants have been shown to increase resistance against *A. hydrophila* in tilapia, carp, catfish, and murrel species by strengthening innate immunity and antioxidant defenses (Galina *et al.*, 2009; Van Hai, 2015; Awad and Awaad, 2017). Elevated levels of lysozyme activity, phagocytosis, respiratory burst responses, and antioxidant enzymes such as superoxide dismutase, catalase, and glutathione peroxidase have frequently been observed following phytotherapeutic supplementation (Elumalai *et al.*, 2020). These findings are particularly important, as oxidative stress and immunosuppression play central roles in the progression of *Aeromonas* infections. (Dadras *et al.*, 2023; Vijayaram *et al.*, 2022) (Pratheepa *et al.*, 2010; Verma *et al.*, 2012; Sutuli *et al.*, 2015; Hardi *et al.*, 2019) (Yin *et al.*, 2009) (Wu *et al.*, 2010) (Harikrishnan *et al.*, 2003)

Despite these promising findings, several constraints remain. Many studies have been limited to laboratory settings and relatively short experimental periods, while comprehensive field trials are comparatively scarce. Moreover, significant variation exists among studies in terms of extraction procedures, plant material used, concentrations, challenge types, fish species, and environmental conditions. This heterogeneity complicates comparisons and underscores the need for standardized experimental models.

Specifically for *Terminalia chebula*, further research is required to evaluate its effectiveness against *Aeromonas hydrophila* infections in *Channa striata*. Current knowledge gaps include optimal dosage, long-term administration effects, pharmacological distribution, toxicity thresholds, and practical application strategies. Additionally, molecular analyses focusing on gene expression, immune signaling cascades, symbiotic bacterial interactions, and transcriptomic processes remain largely unexplored (Reverter *et al.*, 2021).

The reviewed studies collectively demonstrate that medicinal plants can improve fish health through multiple mechanisms, including direct antibacterial activity, immune enhancement, antioxidant protection, and increased disease resistance. Although direct investigations involving *Terminalia chebula* in *Channa striata* remain limited, available evidence strongly supports its potential for future application in murrel aquaculture. The current evidence supporting the application of *Terminalia chebula* against *Aeromonas hydrophila* and its potential effects on fish health is illustrated in Figure 3.

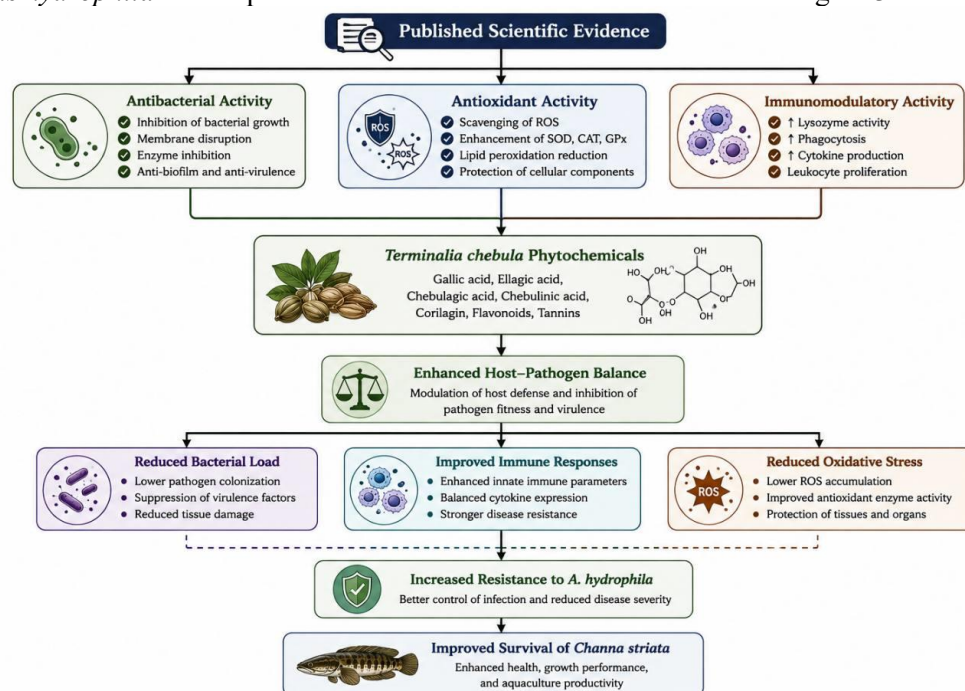


Figure 3. Evidence-based framework illustrating how the antibacterial, antioxidant, and immunomodulatory properties of *Terminalia chebula* may collectively contribute to enhanced resistance against *Aeromonas hydrophila* and improved health outcomes in *Channa striata*. Created by the authors based on information synthesized from the cited literature.

RESEARCH GAPS, CHALLENGES, AND FUTURE PERSPECTIVES

Though ample scientific evidence highlights the antimicrobial, antioxidant, and immunomodulatory properties of *Terminalia chebula*, several key knowledge gaps hinder its practical application in aquaculture. While numerous studies have demonstrated its effectiveness in suppressing diverse microorganisms, relatively few have investigated its specific activity against *Aeromonas hydrophila* under aquaculture conditions (Bag *et al.*, 2013; Kumar *et al.*, 2023; Tiwana *et al.*, 2024). Moreover, most available data are derived from laboratory experiments, making it difficult to predict efficacy in real farm environments (Awad and Awaad, 2017; Van Hai, 2015).

One of the most significant challenges is the lack of standardization. The phytochemical composition of *T. chebula* varies considerably depending on factors such as geographical origin, harvesting time, fruit ripening stage, extraction method, and solvent type (Saleem *et al.*, 2002; Rathinamoorthy and Thilagavathi, 2014). These variations can substantially influence biological activity and contribute to

inconsistencies across studies. Therefore, establishing standardized protocols for extraction, dosage, and experimental design is a critical prerequisite for advancing the commercial application of *Terminalia chebula* in aquaculture, including the optimization of dosage and safety assessment. While low to moderate inclusion rates of herbal extracts have been shown to promote fish growth and enhance immunity, excessively high levels may negatively affect feed acceptability, nutrient metabolism, physiology, and tissue integrity (Citarasu, 2010; Chakraborty and Hancz, 2011). To date, limited studies have evaluated the impact of *T. chebula* supplementation on fish in terms of toxicity, histopathology, reproductive performance, and overall physiology. (Wang *et al.*, 2024; Al-Niaeem *et al.*, 2026)

The mechanisms underlying the antibacterial and immunomodulatory activities of *T. chebula* also require deeper investigation. Although current evidence points to membrane disruption, enzyme inhibition, biofilm suppression, oxidative stress regulation, and immune activation, little is known about the precise signal transduction pathways involved (Kumar *et al.*, 2023; Tiwana *et al.*, 2024). Advanced molecular biology approaches such as transcriptomics, proteomics, metabolomics, and systems biology could provide valuable insights into these processes.

Another area requiring attention is the development of improved delivery systems. Novel technologies such as nanotechnology, microencapsulation, controlled-release formulations, and functional feeds could enhance the stability and efficacy of plant-derived bioactive compounds (Bilia *et al.*, 2014; Yilmaz *et al.*, 2018). Encapsulation, in particular, may protect fragile phytochemicals during feed preparation and ensure targeted delivery to tissues. (Kolygas *et al.*, 2025) (Xue *et al.*, 2026)

In the context of aquaculture, species-specific studies are essential to evaluate the effectiveness of *T. chebula* in murrel (*Channa striata*) culture. Most phytotherapeutic research has focused on tilapia, carp, and catfish, with murels receiving limited attention (Samayanpaulraj *et al.*, 2020). Controlled infection experiments assessing survival rates, immunity, growth performance, antioxidant activity, pathogen load, and economic viability are urgently needed. (Dadras *et al.*, 2023; Al-Niaeem *et al.*, 2026) (Zhu, 2020)

CONCLUSION

The therapeutic potential of *T. chebula* lies in its diverse phytochemical composition, including hydrolyzable tannins, phenolic acids, flavonoids, gallic acid, ellagic acid, chebulagic acid, and chebulinic acid. These compounds contribute to a wide spectrum of biological activities, including antibacterial, antioxidant, anti-inflammatory, and immunomodulatory. Mechanistically, *T. chebula* phytochemicals inhibit bacterial growth through membrane perturbation, enzyme inhibition, biofilm disruption, quorum sensing interference, protein precipitation, and anti-virulence effects. At the same time, they enhance host resilience by boosting innate immunity, modulating inflammatory responses, and maintaining oxidative balance.

Although direct studies on *T. chebula* against *A. hydrophila* in *Channa striata* are limited, existing literature strongly supports its potential as a phytotherapeutic agent in aquaculture. To translate this promise into practice, future research must focus on species-specific challenge trials, standardized extraction and formulation protocols, dosage optimization, toxicity and safety assessments, and large-scale field validation. Advanced omics approaches transcriptomics, proteomics, and metabolomics will be crucial for elucidating molecular mechanisms, while studies on gut microbiome modulation may reveal additional indirect benefits. Furthermore, integrating *T. chebula* with complementary strategies such as probiotics, immunostimulants, functional feeds, vaccines, and improved husbandry practices could maximize its efficacy and reduce dependence on antibiotics.

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