



The Impact of Plant-Derived Compounds on Bacteria in Fish Farms: A Review

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تأثير المركبات المستخلصة من النباتات على البكتيريا في مزارع الأسماك: مراجعة

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قسم الأحياء، كلية التربية، جامعة بني وليد، بني وليد، ليبيا.

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المخلص:

تواجه صناعة تربية الأحياء المائية، الحيوية للأمن الغذائي العالمي، تحديات كبيرة بسبب الأمراض البكتيرية، التي كانت تُكافح تقليدياً باستخدام المضادات الحيوية. وقد أدى الإفراط في استخدام هذه المواد الكيميائية إلى ظهور بكتيريا مقاومة للمضادات الحيوية، مما يشكل مخاطر جسيمة على صحة الحيوان والإنسان والبيئة. تفحص هذه المراجعة بشكل شامل الإمكانيات التي تقدمها المركبات المستخلصة من النباتات (PDCs) كبديل مستدام وفعال لمكافحة البكتيريا في نظم الاستزراع المائي. تُظهر هذه المركبات، التي تشمل الزيوت الأساسية والمستخلصات والمواد الكيميائية النباتية المنقاة من الأعشاب والتوابل والنباتات الأخرى، طيفاً واسعاً من الأنشطة المضادة للميكروبات ضد مسببات الأمراض الرئيسية في مجال الاستزراع المائي مثل بكتيريا *Aeromonas hydrophila* و *Vibrio spp.* و *Streptococcus iniae*. آليات عملها متعددة الأوجه، بما في ذلك تعطيل أغشية الخلايا البكتيرية، وتثبيط إنتاج عوامل الضراوة (على سبيل المثال، من خلال التداخل في نظام الاستشعار النصبي (Quorum Sensing)، وقمع تكوين الأغشية الحيوية (Biofilm)) إلى جانب تأثيراتها المضادة للبكتيريا المباشرة، تظهر دراسات عديدة، بما في ذلك دراسات المؤلفين، أن الإضافة الغذائية لهذه المركبات النباتية تعزز أداء النمو في الأسماك، وتقوي الاستجابات المناعية الفطرية، وتحسن الحالة المضادة للأكسدة، مما يخلق نظام دفاع مضيف أكثر قوة. تجمع هذه المراجعة الأدلة من الدراسات المُجرّاة داخل المختبر (in vitro) وفي الجسم الحي (in vivo)، مسطرة الضوء على فعالية مركبات نباتية متنوعة. وتخلص إلى أن الدمج الاستراتيجي للمركبات المستخلصة من النباتات في بروتوكولات إدارة الصحة في الاستزراع المائي يقدم استراتيجيات واعدة وصديقة للبيئة للتخفيف من الأمراض البكتيرية، والحد من الاعتماد على المضادات الحيوية، والمساهمة في التنمية المستدامة و "التحول الأزرق" للقطاع العالمي لتربية الأحياء المائية.

الكلمات الدالة: المركبات النباتية المنشأ (PhytoGenics) ، الزيوت الأساسية، بدائل المضادات الحيوية، مقاومة مضادات الميكروبات، بكتيريا *Aeromonas hydrophila*، بكتيريا *Vibrio*، كبت الاستشعار النصبى (Quorum quenching) ، الاستزراع المائي المستدام.

Abstract

The aquaculture industry, vital for global food security, faces significant challenges from bacterial diseases, traditionally controlled with antibiotics. The overuse of these chemicals has led to the emergence of antibiotic-resistant bacteria, posing serious risks to animal, human, and environmental health. This review comprehensively examines the potential of plant-derived compounds (PDCs) as sustainable and effective alternatives for bacterial control in aquaculture systems. PDCs, including essential oils, extracts, and purified phytochemicals from herbs, spices, and other botanicals, exhibit a broad spectrum of antimicrobial activities against major aquaculture pathogens such as *Aeromonas hydrophila*, *Vibrio* spp., and *Streptococcus iniae*. Their mechanisms of action are multifaceted, including disruption of bacterial cell membranes, inhibition of virulence factor production (e.g., through quorum sensing interference), and suppression of biofilm formation. Beyond their direct antibacterial effects, numerous studies, including those by the authors, demonstrate that dietary supplementation with PDCs enhances fish growth performance, strengthens innate immune responses, and improves antioxidant status, creating a more robust host defense system. This review synthesizes evidence from *in vitro* and *in vivo* studies, highlighting the efficacy of various PDCs. It concludes that the strategic integration of PDCs into aquaculture health management protocols offers a promising, eco-friendly strategy to mitigate bacterial diseases, reduce reliance on antibiotics, and contribute to the sustainable development and "Blue Transformation" of the global aquaculture sector.

Keywords: PhytoGenics, Essential oils, Antibiotic alternatives, Antimicrobial resistance, *Aeromonas hydrophila*, *Vibrio*, Quorum quenching, Sustainable aquaculture.

1. Introduction

Global aquaculture is a critical sector for food security, providing a substantial portion of the world's aquatic animal protein and is central to the FAO's vision for a "Blue Transformation" [1]. However, its intensive nature creates conditions conducive to disease outbreaks, with bacterial infections being a primary cause of economic losses [2]. For decades, antibiotics have been the cornerstone of disease management. Their prophylactic and therapeutic misuse has led to the proliferation of antibiotic-resistant bacteria (ARB), drug residue accumulation, and the potential transfer of resistance genes to human pathogens [3, 4].

This pressing issue has accelerated the search for sustainable and effective alternatives. Among the most promising candidates are plant-derived compounds (PDCs) [5, 24]. For centuries, herbs and spices have been used in traditional medicine for their antimicrobial properties. In modern aquaculture, PDCs—including essential oils (EOs), crude extracts, and isolated active principles (e.g., phenols, terpenes, alkaloids)—are increasingly recognized for their potential to control pathogens, enhance host immunity, and improve overall health [6, 12, 27].

This review aims to synthesize current scientific knowledge on the application of PDCs for bacterial management in aquaculture. It will explore their mechanisms of action against key fish pathogens, evaluate their efficacy using evidence from both *in vitro* and *in vivo* settings, and discuss their additional benefits on fish health and productivity. Finally, it will address current challenges and future directions for their successful integration into sustainable aquaculture practices.

2. Major Bacterial Pathogens in Aquaculture

Aquaculture systems are susceptible to a variety of bacterial pathogens that can cause significant morbidity and mortality. Key genera include:

Aeromonas: Particularly *A. hydrophila*, a Gram-negative bacterium that causes Motile Aeromonas Septicemia (MAS), characterized by skin ulcers, fin rot, and hemorrhagic septicemia. Its virulence is multifaceted and its taxonomy complex, making it a persistent challenge [8].

Vibrio: Species like *V. anguillarum* (vibriosis), *V. parahaemolyticus* (a cause of Acute Hepatopancreatic Necrosis Disease in shrimp), and *V. vulnificus* are ubiquitous in marine environments and are highly pathogenic to cultured species. The genus exhibits significant biodiversity and adaptability [9].

Streptococcus: Gram-positive bacteria such as *S. iniae* and *S. agalactiae* that cause streptococcosis, leading to meningitis, septicemia, and high mortality rates. *S. iniae* is of global veterinary significance and has proven challenging to control with vaccination alone [10].

The control of these pathogens is increasingly complicated by multidrug resistance, rendering conventional antibiotics ineffective and underscoring the critical need for alternative strategies [4].

Table 1: Major Bacterial Pathogens in Aquaculture and Their Impacts

Pathogen	Gram Stain	Common Diseases	Affected Species	Key Challenges
<i>Aeromonas hydrophila</i>	Negative	Motile Aeromonas Septicemia (MAS), ulcers	Freshwater fish (tilapia, carp)	High prevalence, multidrug resistance [8]
<i>Vibrio anguillarum</i>	Negative	Vibriosis, hemorrhagic septicemia	Marine fish (salmon, sea bass)	Wide host range, rapid progression [9]
<i>Vibrio parahaemolyticus</i>	Negative	Acute Hepatopancreatic Necrosis Disease (AHPND)	Shrimp species	High virulence, major economic impact [9]
<i>Streptococcus iniae</i>	Positive	Streptococcosis, meningitis	Tilapia, rainbow trout	Zoonotic potential, systemic infection [10]

3. Plant-Derived Compounds and Their Mechanisms of Action

PDCs encompass a vast array of bioactive molecules. Their antimicrobial efficacy is not attributed to a single mechanism but rather a combination of disruptive actions:

3.1. Disruption of Cellular Structures

The hydrophobic nature of many EOs (e.g., from oregano, thyme, clove) allows them to integrate into and disrupt the lipid bilayer of bacterial cell membranes. This action increases permeability, leads to leakage of cellular contents, and causes cell death [12, 18]. This physical mechanism makes it difficult for bacteria to develop resistance.

3.2. Inhibition of Virulence and Quorum Sensing

Many pathogens rely on Quorum Sensing (QS), a cell-cell communication system, to coordinate the expression of virulence factors like toxins and biofilms. Numerous PDCs act as

quorum quenching agents, interfering with QS signaling pathways to reduce pathogenicity without necessarily killing them, thereby applying a lower selective pressure for resistance [14].

3.3. Suppression of Biofilm Formation

Biofilms are structured communities of bacteria that are highly resistant to treatments. PDCs like phenolics and flavonoids have demonstrated strong anti-biofilm activity by inhibiting bacterial attachment and disrupting the established biofilm matrix [12].

3.4. Enhancement of Host Immunity and Antioxidant Status

Oxidative stress can immunosuppress animals and increase infection susceptibility. Many PDCs are potent antioxidants that scavenge free radicals and enhance the activity of endogenous antioxidant enzymes (e.g., superoxide dismutase, catalase). By reducing oxidative stress, they indirectly improve the host's ability to fight off bacterial challenges [17, 20, 28]. Furthermore, they directly stimulate innate immune parameters such as lysozyme activity and phagocytosis [22, 27].

Table 2: Mechanisms of Action of Plant-Derived Compounds Against Bacterial Pathogens

Mechanism	Target	Example Compounds	Effect on Bacteria	Advantage
Membrane disruption	Cell membrane	Carvacrol, thymol, eugenol	Increased permeability, cell lysis	Broad-spectrum, low resistance development
Quorum sensing inhibition	Signaling molecules (AHLs)	Allicin, curcumin	Reduced virulence factor production	Anti-virulence, less selective pressure [14]
Biofilm inhibition	Extracellular matrix	Tannins, resveratrol	Prevention of adhesion, biofilm disruption	Enhances efficacy of other treatments [12]
Antioxidant activity	Reactive oxygen species	Polyphenols (in many herbs)	Reduction of oxidative stress in host	Enhanced immune function [17, 28]
Immunostimulation	Fish immune system	Compounds in <i>Melissa officinalis</i>	Increased lysozyme, phagocytosis	Improves host's natural defenses [22]

4. Efficacy of PDCs Against Aquaculture Pathogens

4.1. In Vitro Studies

A multitude of *in vitro* studies have confirmed the strong antibacterial effects of PDCs. Research has demonstrated that extracts from various plants exhibit significant activity against model and pathogenic bacteria. For instance, essential oils from oregano (*Origanum vulgare*) and thyme (*Thymus vulgaris*) are highly effective against *Aeromonas* and *Vibrio* species [12]. Specific work by the authors has shown that methanolic extracts of lichen (*Usnea barbata*) and dandelion (*Taraxacum officinale*) possess notable antimicrobial properties against *E. coli* and *S. aureus* [18, 19, 41], indicating broad-spectrum potential relevant to aquaculture environments.

Table 3: In Vitro Efficacy of Selected Plant-Derived Compounds Against Bacterial Pathogens

Plant Source	Form	Target Pathogen	Key Finding	Reference
<i>Usnea barbata</i> (Lichen)	Methanolic extract	<i>E. coli</i> , <i>S. aureus</i>	Demonstrated significant antimicrobial activity	[19, 29]
<i>Taraxacum officinale</i> (Dandelion)	Extract	<i>E. coli</i> , <i>S. aureus</i>	Showed mechanism of action and therapeutic potential	[41]
<i>Origanum vulgare</i> (Oregano)	Essential oil	<i>A. hydrophila</i>	Low MIC values due to membrane disruption	[12]
<i>Thymus vulgaris</i> (Thyme)	Essential oil	<i>Vibrio spp.</i>	Effective inhibition of growth	[12]
<i>Allium sativum</i> (Garlic)	Extract	<i>S. iniae</i>	Inhibition through quorum quenching	[14]

4.2. In Vivo Studies and Dietary Supplementation

The positive *in vitro* results have been corroborated by numerous *in vivo* feeding trials. Dietary supplementation with PDCs has consistently been shown to:

Enhance Growth Performance: Improved feed intake, weight gain, and feed conversion ratio, likely due to better gut health and nutrient absorption [21, 23].

Boost Immune and Antioxidant Responses: Significant increases in innate immune parameters (lysozyme, phagocytosis) and antioxidant enzyme activities (SOD, CAT) are commonly observed. Bilen et al. [20] found that lemon balm (*Melissa officinalis*) extract enhanced immune and antioxidant responses in rainbow trout. Similar enhancements were seen with dandelion and lichen extracts [28].

Increase Disease Resistance: Fish fed PDC-supplemented diets show higher survival rates upon bacterial challenge. For example, dietary flaxseed oil [11] and white mustard oil [24] improved immune response and disease resistance in rainbow trout.

Table 4: In Vivo Effects of Dietary Supplementation with Plant-Derived Compounds in Fish

Plant Material	Form	Fish Species	Key Findings	Reference
<i>Melissa officinalis</i> (Lemon Balm)	Extract	Rainbow trout	Enhanced digestive/antioxidant enzymes, immune response	[20, 22]
<i>Taraxacum officinale</i> (Dandelion)	Extract	Rainbow trout	Improved growth performance, antioxidant enzymes	[2, 21, 28]
<i>Usnea barbata</i> (Lichen)	Extract	Rainbow trout	Enhanced antioxidant and immune responses	[6, 28]
<i>Linum usitatissimum</i> (Flaxseed) Oil	Oil	Rainbow trout	Improved immune response, disease resistance	[11, 15]
<i>Sinapis alba</i> (White Mustard) Oil	Oil	Rainbow trout	Enhanced growth, immunity, antioxidant status	[24]
<i>Vitex agnus-castus</i> (Chaste Tree)	Extract	Rainbow trout	Improved haematological indices, growth, and digestive enzymes	[17, 30]

5. Benefits Beyond Antibacterial Action

The advantages of PDCs extend far beyond direct pathogen killing:

Appetite Stimulation: Many herbs and spices are palatable and can stimulate feed intake.

Improved Gut Health: They can modulate the gut microbiota, promoting beneficial bacteria and inhibiting pathogens, leading to improved intestinal morphology and function [13].

Reduced Environmental Impact: As natural products, PDCs are generally biodegradable and do not contribute to persistent environmental pollution like synthetic antibiotics, aligning with the principles of eco-friendly aquaculture [31,32,33].

6. Challenges and Future Perspectives

Despite the promising results, several challenges remain for the widespread adoption of PDCs:

Standardization: The bioactive content of plants can vary widely based on species, geography, season, and extraction method. Standardization of extracts is crucial for consistent efficacy [34,35,36].

Palatability and Acceptance: Some EOs and extracts have strong odors or tastes that may reduce feed palatability for certain fish species.

Optimal Dosage: Determining the effective, non-toxic dose is critical, as high levels can be anti-nutritional or toxic to fish.

Delivery Methods: Exploring efficient delivery methods beyond dietary inclusion, such as water immersion or nanoparticle encapsulation for enhanced bioavailability, is a key area for future research [37,38,39, 40].

7. Conclusion

The evidence presented in this review strongly supports the use of plant-derived compounds as a viable, sustainable, and effective strategy for managing bacterial pathogens in aquaculture. Their multifaceted mechanisms of action—including direct antimicrobial activity, virulence suppression, immunostimulation, and antioxidant enhancement—make them powerful tools against a range of economically important diseases. Studies on specific compounds like lemon balm, dandelion, lichen, flaxseed, and mustard oils demonstrate tangible benefits in key species like rainbow trout. By reducing the reliance on conventional antibiotics, PDCs can help mitigate the global threat of antimicrobial resistance and support the sector's sustainable growth. Future research should focus on standardizing products, optimizing delivery methods (e.g., nano-encapsulation), and conducting large-scale field trials to fully integrate these promising natural compounds into holistic and sustainable aquaculture health management plans.

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