Aquaculture International (2022) 30:1239–1259
https://doi.org/10.1007/s10499-022-00841-7

Medicinal herbs and phytochemicals to combat pathogens in aquaculture

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Received: 7 September 2021 / Accepted: 10 January 2022 / Published online: 19 February 2022
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Abstract

The global production of aquaculture has grown rapidly and is dominated by China, Vietnam, and other East Asian countries. The use of antibiotics is widespread in the aquaculture industry but has been slowly decreasing as the benefits of medicinal herbs become clear. Various medicinal herbs are known to have excellent properties, such as antiviral, antibacterial, and antifungal activity; hormonal balancing; and physiological support (immune and digestive systems). The aim of this paper is to review the latest scientific information on the application of medicinal herbs in different aquaculture sectors, including marine, freshwater and crustacean culture, and the potential problems and recommendations for the application of medicinal herbs in aquaculture, to provide clues for the development of medicinal herbs for epidemic disease resistance of aquaculture industry in the future.

Keywords Aquaculture · Medicinal herbs · Phytochemicals · Inhibitory activity against pathogens · Physiological support

Handling Editor: Dr. Gavin Burnell

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Introduction

Current aquaculture status

Global production of aquaculture has grown rapidly and is dominated by China, Vietnam, and other East Asian countries (FAO 2018; Sahoo and Goodwin 2012). A recent report from FAO (2018) stated that world fish production reached a peak of about 171 million tonnes in 2016, with aquaculture sectors contributing 47% of the total fisheries production. The income from aquaculture and fisheries production in 2016 was USD $362 billion, of which USD $232 billion was from the aquaculture sector. Carp (*Cyprinidae*) contributed the highest portion (39%) of the total cultured finfish, followed by Atlantic salmon and catfish (*Pangasius* spp.). Crustaceans such as shrimp have high commercial value, are intensely traded, and are a special commodity in the aquaculture industry.

Aquaculture is the only way to maintain the supply of fish when the production of wild fisheries declines (Syahidah et al. 2015). The aquaculture sector has taken this responsibility seriously, as indicated by the continuing and impressive growth of the supply of aquatic organisms for human consumption. With the increasing demand for aquatic products, the aquaculture industry is striving to increase its output through intensifying culture density, modernizing culture systems, and utilizing high-end technology. However, the industry frequently faces problems such as unstable fish feed prices, environmental issues, and infectious diseases.

Major pathogens in aquaculture

The aquaculture and fisheries sector is vulnerable to new and emerging pathogenic diseases. In 2016, infectious diseases were the most serious problem affecting global aquaculture production, and they resulted in severe economic losses. Infectious diseases are caused by intensive culture and stressful rearing conditions that make cultured fish vulnerable to different pathogens. Bacteria, parasites, and viruses all cause infectious diseases in the aquaculture industry, which is a major concern to aquaculture stakeholders, and many aquaculture industries have collapsed due to infectious diseases (Li et al. 2018, 2019b). Viral outbreaks have become a significant barrier for the aquaculture industry and the continuity of biodiversity in the native environment (Sahoo and Goodwin 2012). Major viral infections in marine fish are caused by members of the Iridoviridae family, including red sea bream iridovirus, grouper iridovirus, rock bream iridovirus, and sea bass iridovirus (Chinchar et al. 2017; Do et al. 2004; Qin et al. 2003; Xiao et al. 2019a). Rhabdoviridae diseases, such as infectious hematopoietic necrosis virus, is economically important in many salmonid species (Chinchar et al. 2017; Dixon et al. 2016; Do et al. 2004; Qin et al. 2003; Xiao et al. 2019a). Spring viremia virus, a member of the Rhabdoviridae family, is highly contagious for juvenile fish (Bernoth and Crane 1995; Song et al. 2020). Other freshwater viral diseases, such as Koi herpes virus, infectious pancreatic necrosis, viral hemorrhagic septicemia virus, and Cyprinid Herpesvirus 2 have also posed a significant threat to the aquaculture industry (Davison et al. 2009; Eun-Hye et al. 2015; Flores-Mara et al. 2017; Hedrick et al. 2005; Tang et al. 2020). Shrimp production is being threatened by significant diseases of crustaceans, including white spot syndrome virus (WSSV) (Clark 2016), shrimp hemocyte iridescent virus (SHIV) disease, early mortality syndrome (EMS) (Lightner et al. 2012), acute hepatopancreatic necrosis disease (AHPND) (Chaweepack et al. 2015), hepatopancreas necrosis syndrome (HPNS) (Huang et al. 2016) and recent study has shown that intestinal microbiota dysbiosis lead to shrimp white feces syndrome (WFS) (Huang et al. 2020). These diseases have led to catastrophic economic losses annually to the global shrimp aquaculture industry (Stentiford et al. 2012).

High value commercial aquaculture species are often infected by bacteria (Michael et al. 2018; Yu et al. 2018). For example, vibriosis is known to infect many marine, freshwater, and crustacean culture systems all over the world. There are several known zoonotic vibrios, including warm-water *Vibrio vulnificus*, *V. alginolyticus*, and *Photobacterium damselae*. *Aeromonas* spp. can infect several freshwater, brackish water, and marine cultured species.

Parasitic pathogens cause severe damage to the aquaculture industry. Most parasitic diseases have a strong relationship with the management of the culture environment and water. Several parasites have been reported in marine fish, including the myxozoans *Myxobolus cerebralis* and *Tetracapsuloides bryosalmonae* (Michael et al. 2018). Enterocytozoon hepatopenaei (EHP) is the severe infectious diseases in shrimp culture (Rajendran et al. 2016) *Argulus japonica*, *Saprolegnia*, and *Ichthyophthirius multifiliis* are commonly found in freshwater aquaculture (Muhamd et al. 2014). Approaches to prevent infectious diseases include antibiotics, vaccines, chemotherapeutic agents, and immunostimulants (Baleta et al. 2013; Chen et al. 2016; Dügenci et al. 2003; Suwaree et al. 2013). The application of antibiotics in aquaculture has been prohibited by many countries due to their negative effects on the biotic environment and on humans. Unlike vertebrates, invertebrates such as shrimp, typically lack acquired immunity, and depend on innate immune systems to defend against infections (Nyholm and Graf 2012; Zuo et al. 2020). For vertebrates, the use of vaccines is recognized as a potentially effective strategy (Liu et al. 2015; Shin et al. 2013). However, vaccines are frequently used prophylactically but not as treatments of aquatic diseases.

Medicinal herbs applications in aquaculture

Medicinal herbs and their ingredients have been widely used by humans for thousands of years (Guo et al. 2018; Shi et al. 2012; Tan and Vanitha 2004; Zeng et al. 2012). More than 60 different medicinal herb species have been applied to treat aquatic diseases in aquaculture (Bulfon et al. 2015). Countries with long histories of civilization, including China, India, South and Central America, and Southeast Asia, are known to use these therapeutic methods. In Western countries, the medical application of medicinal plants and herbs is also acknowledged. In recent years, public awareness about using medicinal herbs instead of chemical drugs has significantly increased. Various medicinal herbs are known to have properties such as antiviral, antibacterial, and antifungal activities; hormonal balancing; and physiological support (immune and digestive systems) (Fig. 1) (Adel et al. 2015; Giri et al. 2019; Liu et al. 2019b, 2020c; Qiu et al. 2020; Rajeswari et al. 2012). More and more researches have been focused on the mechanism of anti-pathogenic in medicinal plants. Previous studies have shown that anti-virus mechanisms of medicinal plants have direct antiviral activity, such as inhibiting viral attachment, entry, replication, assembly and budding (Li and Peng 2013). Medicinal plants can directly promote the production of antibodies and participate in the specific immune response of fish in the process of pathogen infection. Many studies have shown that the anti-bacterial activity of medicinal plants and their active

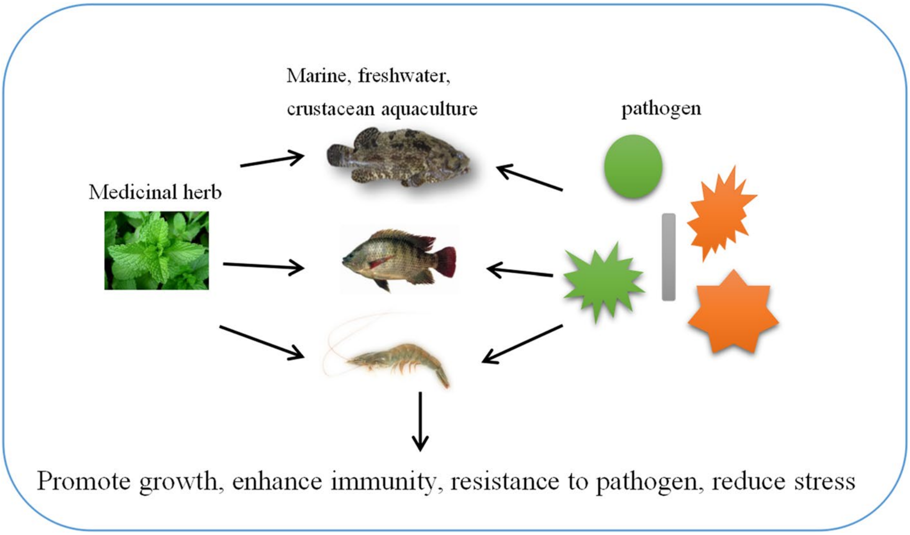

Fig. 1 Illustration of the benefits of application of medicinal herbs in aquaculture

compounds has multiple mechanisms, including inhibition of microbial energy and protein synthesis, destruction of cell membranes, inhibit biofilm formation and DNA replication, cell wall biosynthesis, promote the production of reactive oxygen species, inhibition of metabolic pathways (Khameneh et al. 2019; Awolola et al. 2014; Górniak et al. 2019; Ghosh et al. 2021). For instance, diets supplemented with medicinal herbs leaves extract (such as *Mitracarpus scaber*, *Tridax procumbens*) promoted fish growth performance, antioxidants, non-specific immunity and resistance of *Nile tilapia* to parasitic infection (Adeshina et al. 2021a, b). Researchers have reported that these plant-based ingredients have many beneficial effects and may act as growth promoters, immunostimulants, feeding attractants, tonics, and antistress agents Awad and Awaad 2017; Citarasu 2010; Liu et al. 2019a; Syahidah et al. 2015; Hamed et al. 2021). These compounds also are nontoxic, biodegradable, and biocompatible, and plant-based medicines lack the significant negative effects of antibiotics (Table 1) (Li et al. 2019b). Moreover, the medicinal herbs mixtures was synergistic and additive effects against parasitic (*Ichthyophthirius multifiliis*) infection in grass carp (Fu et al. 2021). Recent study has shown that *Acanthopanax senticosus* improves growth performance, immunity and antioxidant capacity by regulating lipid metabolism in *Oreochromis niloticus* (Li et al. 2021). Water hyacinth leaves extracts enhances disease resistance in *Channa punctata* from *Vibrio harveyi* infection (Verma et al. 2021). There have been many studies about the applications of medicinal herbs as growth promoters, immunostimulants, and antibacterial agents in aquaculture (Galina et al. 2009; Hai 2015; Li et al. 2021; Pandey et al. 2012; Pu et al. 2017; Reverter et al. 2014; Stratev et al. 2018).

Herein, we provide an overview of the effectiveness of medicinal herbs in different aquaculture sectors (e.g., marine, freshwater, and crustacean culture), and we also focus on the potential applications, benefits, problems, and future recommendations for the use of medicinal herbs in aquaculture.

Table 1 Application of medicinal plants in aquaculture

Name	Extracts	Effects	References
Sophora flavescens	Alkaloid	Resistance to parasite (*Trichodina*)	Zhang et al. 2004
Rosa chinensis Jacq.	Gallic acid	Resistance to bacteria (*V. anguillarum*, *V. harveyi*, *V. parahaemolyticus* and *V. vulnificus*)	Li et al. 2007
Nyctanthes arbortristis seed	Chloroform extract	Enhance immunity	Kirubakaran et al. 2010
Kalopanax pictus	Ethanol extract	Enhance immunity, improve antibacterial ability	Harikrishnan et al. 2011
Eriobotrya japonica	Ethanol extract	Enhance immunity, improve antibacterial ability	Kim et al. 2011
Siegesbeckia glabrescens	Ethanol extract	Enhance immunity, improve antibacterial ability	Harikrishnan et al. 2012
Salvadora persica L.	Aqueous extract	Resistance to bacteria, bacteria, fungal, plasmodia	Ahmad et al. 2013
Honeysuckle	Feed medicine additive	Promote growth and survival of *P. monodon*	Chen et al. 2013
Gynura bicolor	Aqueous extract	Resistance to bacteria (*V. alginolyticus*)	Hsieh et al. 2013
Nigella sativa and *Quercetin*	Feed medicine additive	Enhance immunity	Awad et al. 2013
Psidium guajava L.	Feed medicine additive	Antiviral and antibacterial activity	Yin et al. 2014
Agathi grandiflora	Methanolic extracts	Resistance to virus (white spot syndrome virus)	Bindhu et al. 2014
Mentha piperita	Ethanol extract	Enhance immunity	Adel et al. 2015
Allium cepa	Feed medicine additive	Promote growth, enhance immunity	Akrami et al. 2015
Lonicera japonica Thunb.	Aqueous extract	Enhance immunity	Kwon et al. 2015
Astragalus membranaceus and *Glycyrrhiza glabra*	Feed medicine additive	Promote growth, antioxidant and enhance immunity	Elabd et al. 2016
Camellia sinensis	Feed medicine additive	Enhance immunity and resistance against *P. damselae*	Kakoolaki et al. 2016
Green tea	(-)-epigallocatechin-3-gallate	Resistance to virus (Grass carp reovirus)	Wang et al. 2016

Table 1 (continued)

Name	Extracts	Effects	References
Plantago asiatica, Houttuynia cordata, and Mentha haplocalyx	Feed medicine additive	Enhance immunity	Wu et al. 2016
Nigella sativa	Feed medicine additive	Promote growth, enhance immunity	Altunoglu et al. 2017
Allium cepa and Zingiber officinale	Feed medicine additive	enhancing stress tolerance upon infecti with *V. harveyi*	Amar et al. 2018
Magnolia officinalis Rehd et Wils.	Magnolol and honokiol	Resistance to virus (grass carp reovirus)	Chen et al. 2017
Rosa canina and *Carthamus tinctorius*	Feed medicine additive	Promote growth, enhance immunity	Dadras et al. 2017
Rigonella foenum graecum	Feed medicine additive	Antioxidants	Guardiola et al. 2017
Curcumin	Curcumin	Resistance to parasitic(Ichthyophthirius multifiliis)	Liu et al. 2017
Lonicera japonica Thunb.	Ethanol extract, Aqueous extract	Resistance to bacteria (*Proteus mirabilis*)	Xie et al. 2017
Piaractus mesopotamicus	Feed medicine additive	Resistance to bacteria (*A. hydrophil*a)	Zanuzzo et al. 2017
Medlar	Ethanol extract	Enhance immunity	Hoseinifar et al. 2017
Olea europea L.	Ethanol extract	Promote growth, enhance immunity	Baba et al. 2018
Withania sominefera	Feed medicine additive	Resistance to bacteria (A. Hydrophila)	Eman et al. 2018
Trachinotus ovatus	Feed medicine additive	improving intestine morphology, immunity, antioxidant abilities and intestinal barrier	Tan et al. 2018
Green tea	(-)-epigallocatechin-3-gallate	Resistance to virus(White spot syndrome virus)	Wang et al. 2018
enrofloxacin and San-Huang-San	Feed medicine additive	Improve immunity and disease resistance	Zhai et al. 2019
icariin	Feed medicine additive	Antioxidant and non-specific immunity.	Zheng et al. 2019
Radix Bupleuri extracts	Feed medicine additive	Enhance immunity	Zou et al. 2019
Thlaspi arvense Linn.	Aqueous extract	Resistance to virus (grouper iridovirus)	Xiao et al. 2019b
Oliveria decumbens	Feed medicine additive	antibacterial, immunostimulatory and antioxidant properties	Vazirzadeh et al. 2019
Lemon peels	Feed medicine additive	Enhance immunity	Rahman et al. 2019b
rosemary leaf powder	Feed medicine additive	Enhance antioxidant and immunological	Yousefi et al. 2019

Table 1 (continued)

Name	Extracts	Effects	References
Viola philippica	Aqueous extract	Resistance to virus (grouper iridovirus)	Yu et al. 2019a
Moringa oleifera	Feed medicine additive	Promote growth, enhance immunity and prevents high ammonia stress	Kaleo et al. 2019
Ziziphus jujuba Mill.	Feed medicine additive	Promote skin mucosal immunity and fingerlings performance	Hoseinifar et al. 2019
Ginkgo biloba	Feed medicine additive	Resistance to bacteria (*A. Hydrophila*)	Bao et al. 2019
Gardenia jasminoides	Injection	Resistance to virus (white spot syndrome virus)	Huang et al. 2019
Rose myrtle *Rhodomyrtus tomentosa* seed	Aqueous extract	Resistance to disease (Acute hepatopancreatic necrosis disease)	Dang et al. 2019
Boesenbergia rotunda	Feed medicine additive	Promote growth, enhance immunity	Doan et al. 2019a, b
Camellia sinensis	Feed medicine additive	Promote growth, enhance immunity and resistance against *Streptococcus agalactiae*	Doan et al. 2019a, b
Cotinus coggygria and *Malva sylvestris*	Aqueous methanolic extracts	Promote growth, enhance immunity	Bilen et al. 2019
Coriandrum sativum	Feed medicine additive	Promote growth, enhance immunity and resistance against *Yersinia ruckeri*	Farsani et al. 2019
Allium sativum	Feed medicine additive	Enhance immunity, prevention of *Tilapia streptococcus iniae* infection	Foysal et al. 2019
Turmeric	Curcumin	Promote growth, antioxidant and resistance against *Aeromonas hydrophila*	Giri et al. 2019
Coptis chinensis Franch.	Aqueous extract	Resistance to bacteria (*Vibrio alginolyticus* from *Trachinotus ovatus*)	Liu et al. 2019b
Illicium verum Hook. f.	Aqueous extract, shikimic acid, trans-anethole, 3,4-dihydroxybenzoic acid, quercetin	Resistance to virus (grouper iridovirus)	Liu et al. 2020a
Lonicera japonica Thunb.	Aqueous extract, Isochlorogenic acid (A, B, C), Inositol, Caffeic acid, Luteolin	Resistance to virus (grouper iridovirus)	Liu et al. 2020b
Curcuma kwangsiensis	Ethanol extract, Curcumol, Curcumin, Curcumenol, Curdione	Resistance to virus (grouper iridovirus)	Liu et al. 2020c

Table 1 (continued)

Name	Extracts	Effects	References
Mentha longifolia	Hydroalcoholic extract	Promote growth, enhance immunity and resistance against *Yersinia ruckeri*	Heydari et al. 2020
Scutellaria baicalensis	Water extract	Promote growth	Xia et al. 2021
Cynanchum atratum and *Sophora flavescens*	Ethanol extract	against Ichthyophthirius multifiliis in grass carp	Fu et al. 2021
Mitracarpus scaber leaves extract	Hot-extracted using 80% ethanol	improved growth, antioxidants, non-specific immunity, and resistance to Gyrodactylus malalai infestation	Adeshina et al. 2021a
Tridax procumbens leaves extract	Extracted with 80% ethanol	stimulated growth, antioxidants, immunity, and resistance of Nile tilapia, to monogenean parasitic infection	Adeshina et al. 2021b
Astragalus polysaccharides	co-supplementation with probiotics and Chinese herb polysaccharides	enhanced immunity and disease resistance, and modulated intestinal microbiota	Fan et al. 2021
Canthopanax senticosus	Feed medicine additive	improves growth performance, antioxidant, and immune capacity	Li et al. 2021
Allicin	Feed medicine additive	enhanced biochemical, and immunity	Hamed et al. 2021
Water hyacinth (Eichhornia crassipes) leaves	ethanol and methanol extracts	enhance fish immunity and disease resistance against the *Vibrio harveyi* infection.	Verma et al. 2021
Magnolol	Ethyl acetate extract	against *Ichthyophthirius multififiliis* infection	Zhang et al. 2022

Applications of medicinal herbs in mariculture

Studies of the use of medicinal herbs in mariculture have been widely reported (Li et al. 2019b; Pu et al. 2017). The fishery sector has gradually shifted from the use of antibiotics to environmentally friendly therapeutic methods. Adverse impacts on humans and the environment are a major cause of this transition. Additionally, simple application is one of the driving factors in the use of medicinal herbs in aquaculture. Other factors that contribute to wide applications of medicinal herbs are easy acquisition, fewer negative impacts, and low prices. Medicinal herbs have been applied in the culture of several economically important marine fish, including grouper, rainbow trout, sea bass, snapper, and salmon. Growth measurement, immune function tests, and challenge with pathogens are used to check the efficacy of plant-based medicines.

Medicinal herbs can be used in their crude form or as herbal extracts, active materials, and in mixtures with other materials (Awad and Awaad 2017). Recent studies reported that *Curcuma kwangsinesis* active ingredients (Liu et al. 2020c) and extracts of *Lonicera japonica* Thunb. (Liu et al. 2020b), *Illicium verum* Hook. f. (Liu et al. 2020a), *Thlaspi arvense* Linn. (Xiao et al. 2019b), and *Viola Philippica* (Yu et al. 2019a) could inhibit grouper iridovirus infection *in vitro* and *in vivo*. Application of *Radix bupleuri* extracts in the hybrid grouper (*Epinephelus lanceolatus*♂ × *E. fuscoguttatus*♀) potentially contributed to hepatoprotective activity as well as immune responses (Zou et al. 2019). The addition of dandelion extracts to the diet showed effects on intestinal morphology, antioxidant status, immune function, and physical barrier function of juvenile golden pompano (Tan et al. 2018b). Other studies showed that the use of *Ginkgo biloba* leaf extracts (Tan et al. 2018a), *Panax notoginseng* extracts, *Lycium barbarum* extracts (Sun et al. 2018), and *Senecio scandens buch-ham* extracts (Sun et al. 2020) could enhance the hepatic antioxidant and liver-protecting effects in hybrid grouper.

The onion *Allium cepa* and ginger *Zingiber officinale* contain phytochemicals that have many health benefits. Amar et al. (2018) reported that *A. cepa* and *Z. officinale* supplements in the diet can have stress protective and survival effects in brown-marbled grouper (*E. fuscoguttatus*) challenged with *V. harveyi* JML1 (Amar et al. 2018). Other researchers reported that feeding groupers with medicinal plants such as *Siegesbeckia glabrescens, Kalopanax pictus*, and *Eriobotrya japonica* extract significantly increased their immune parameters, disease resistance, and survival rate against vibriosis (Harikrishnan et al. 2011, 2012; Kim et al. 2011). Heydari et al. (2019) reported that feeding rainbow trout with 0.2% horsemint (*Mentha longifolia*) significantly improved their hematological and mucosal immunity indices and increased expression of immune-related genes such as *TNF-α* and lysozyme resistance to the bacterium *Yersinia ruckeri* (Heydari et al. 2020). Dietary supplementation with aloe vera (*Aloe barbadensis*) powder at 15 g/kg significantly enhanced the growth performance and immune parameters of rainbow trout and boosted their resistance against *S. parasitica* infection (Mehrabi et al. 2019; Farsani et al. 2019) claimed that dietary administration of *Coriandrum sativum* extracts in rainbow trout significantly improved their growth parameters, immunological status, and parasitic resistance against *Y. ruckeri* infection.

The olive plant is another medicinal herb that has health boosting properties and a long history of use in human therapeutics. Dietary supplementation with olive leaves (*Olea europea* L.) in rainbow trout increased serum biochemical parameters, survival rate, and immune-related gene expression (Baba et al. 2018). Black cumin seed (*Nigella sativa*) has been used for thousands of years as a spice and food preservative and as a protective and therapeutic remedy for numerous diseases (Dorucu and Celayir 2009). The plant is widely distributed in Southern Europe, Northern Africa, and Asia. The application of *N. sativa* in rainbow trout aquaculture has been reported. For example, Awad et al. (2013) reported that incorporation of *N. sativa* in the feed provoked the immune system of rainbow trout and had no significant effect on the growth performance of fish (Altunoglu et al. 2017; Hedrick et al. 2005; Adel et al. 2015) reported that peppermint (*Mentha piperita*) extracts could induce growth and enhance immune parameters (systemic and mucosal level) of Caspian brown trout (*Salmo trutta caspius* Kessler, 1877), and Sheikhzade et al. (2011) found that decaffeinated green tea (*Camellia sinensis*) in small doses could improve the immune performance of rainbow trout. Minerva et al. (2019) evaluated the dietary administration of *Chenopodium ambrosioides* L. in Pacific red snapper (*Lutjanus peru*) and reported immunostimulant and antimicrobial activities in skin mucus against *V. parahaemolyticus* and *Aeromonas hydrophila*. The marine longfin yellowtail (*Seriola rivoliana*) exposed to hawthorn (*Crataegus mexicana*) showed enhanced antioxidant and immunological parameters in leukocytes (Martha et al. 2019; Bilen et al. 2019) showed that dietary supplementation with tetra (*Cotinus coggygria*) and common mallow (*Malva sylvestris*) extracts improved the immune response in gilthead sea bream (*Sparus aurata*) and European sea bass (*Dicentrarchus labrax*). Beltrán et al. (2018) examined the effects of *Origanum vulgare* L. extracts on *S. aurata* and found that aqueous and ethanol leaf extracts had immunostimulant, cytotoxic, bactericidal, and antioxidant properties. Guardiola et al. (2017) showed that dietary administration of fenugreek (*Trigonella foenum graecum*) seeds alone or mixed with Gram-positive *Bacillus licheniformis*, *Lactobacillus plantarum*, or *Bacillus subtilis* had antioxidant activity in gilthead sea bream. Kakoolaki et al. (2016) reported that dietary supplementation with *C. sinensis* leaf extracts at 100 and 200 mg/kg significantly increased the immune activities and resistant against *P. damselae* in *Mugil cephalus*.

Several studies tested medicinal herb applications in beluga (*Huso huso*), which is the largest species of sturgeon and an economically important species in the Caspian Sea (Jalali et al. 2010; Akrami et al. 2015) showed that dietary onion (*A. cepa*) powder significantly improved growth performance, immune response, and hemato-biochemical parameters of juvenile beluga. Dietary intake of rose hip (*Rosa canina*) and safflower (*Carthamus tinctorius*) did not affect growth performance, but both herbs enhanced the immune response and physiological parameters of Persian sturgeon (Dadras et al. 2016; Adel et al. 2015) reported that dietary administration of peppermint (*M. piperita* L.) in fry of Caspian white fish (*Rutilus frisii kutum*) promoted growth performance and increased hematological parameters (red and white cell number, hematocrit content, and serum hemoglobin) and humoral immunity (both mucosal and systemic). Barramundi (*Lates calcarifer*) is a commercially important fish in mariculture, and its culture in marine net cages is a well-known fish farming method worldwide. Shiu et al. (2016) showed that a diet containing 5% *Citrus depressa Hayata* leaf meal provoked the innate immune response and pathogen resistance against *A. hydrophila* in barramundi (Shiu et al. 2016; Talpur and Ikhwanuddin 2013) reported that dietary administration of *Azadirachta indica* leaf induced immunological activity, hematological parameters, and blood biochemical indices against *V. harveyi*, and increased survival rate in *L. calcarifer* (Talpur and Ikhwanuddin 2013). Other scientists have reported the effects of medicinal herbs *Plantago asiatica*, *Houttuynia cordata*, and *Mentha haplocalyx* in cobia (*Rachycentron canadum*). The results demonstrated these herbs did not significantly affect growth performance, but they did stimulate phagocytosis, superoxide dismutase, reactive oxygen species, and lysozyme activity (Wu et al. 2016).

Benefits of medicinal herbs in freshwater aquaculture

Studies of the use of medicinal herbs in freshwater fish have made an important contribution to the application of medicinal herbs in aquaculture. Freshwater aquaculture species for which medicinal herbs have been applied include tilapia, carp, and catfish. The effects of medicinal herb exposure on growth performance, immune status, and antiviral and antibacterial activity have been reported for some species. Nile tilapia (*Oreochromis niloticus*) exposed to dietary supplementation with Thai ginseng (*Boesenbergia rotunda*) powder at 10 g/kg showed improved growth performance and immune response (Doan et al. 2019a). Furthermore, supplementation with elephant's foot (*Elephantopus scaber*) extracts at 5 g/kg promoted growth, improved humoral and mucosal immunity, and supported disease resistance against *Streptococcus agalactiae* infection. Ahmad and Rajagopal (2013) studied the effects of Miswak *(Salvadora persica L.*), a medicinal plant with a long medicinal history for oral hygiene, on tilapia culture. Nile tilapia fed a basal diet supplemented with Miswak showed significant improvements in immune response and protective ability (Mohamed et al. 2019; Foysal et al. 2019) reported that garlic (*Allium sativum*) supplementation could control *Streptococcus iniae* infection in tilapia. Abdel et al. (2019) reported that dietary intake of lemon peel (*Citrus limon* L. Burm.) had significant effects on antioxidant and immune responses of Nile tilapia and had no effect on fish growth (Rahman et al. 2019b).

Different herbs have different effects on growth performance. A diet supplemented with fenugreek seed powder improved the growth and feed efficiency of tilapia and also upregulated the immune-related gene expression of fish challenged with *A. hydrophila* (Moustafa et al. 2020; Doan et al. 2019b) showed that dietary supplementation with Assam tea extracts at 2 g/kg enhanced the growth rate and reduced the feed conversion ratio, significantly improved the skin mucus and serum, and improved immunity against *Streptococcus agalactiae* infection in Nile tilapia. The Indian lotus (*Nelumbo nucifera* Gaertn.) leaf is a medicinal plant that contains several pharmacological materials. In tilapia challenged with heavy metals (a combination of Hg, Pb, Zn, and Cd), dietary supplementation with Indian lotus ameliorated lipid peroxidation, oxidative stress, and histological changes, and protected the fish against the toxic effects of the heavy metals (Rahman et al. 2019a). Administration of different derivatives of *Oliveria decumbens* protected tilapia from *S. iniae* infection and enhanced their immunity (Vazirzadeh et al. 2019). Mustafa et al. (2017) found that dietary supplementation with *Cucurbita mixta* L. seed meal at 4 and 6 g/kg resulted in improved growth performance, innate immunity, and bacterial resistance against *A. hydrophila* in *Oreochromis mossambicus*. Additionally, *Withania sominefera* root powder added to the tilapia diet at 5% concentration improved resistance against *A. hydrophilla* and increased survival rate (Eman et al. 2018).

The application of medicinal herbs to cyprinid aquaculture has been widely studied. Experiments have shown that rosemary (*Rosmarinus officinalis*) has antioxidant, anti-inflammatory, antithrombotic, hepatoprotective, antidiabetic, diuretic, anticancer, and antinociceptive activities in animals and humans (Neves et al. 2018; Oliveira et al. 2019; Yousefi et al. 2019) showed that oral administration of rosemary leaf powder promoted growth parameters, enhanced immunological and antioxidant status, and reduced the stress effects of density crowding of common carp fingerlings. They also found that the common carp diet supplemented with lavender (*Lavandula angustifolia*) extract at 1.0-1.5% significantly suppressed stress, inflammation, and oxidative conditions and augmented the immune system. *Ginkgo biloba* leaf is another traditional medicine that is widely used in China. Common carp diet enriched with 10 g/kg *G. biloba* leaf extract effectively promoted growth performance, modulated immune-related gene expression, and improved survival rate after *A. hydrophila* infection (Bao et al. 2019). Turmeric (*Curcuma longa* L) is a popular herb that is widely used in Indian culture. The addition of its active ingredient, curcumin, to the carp diet at 15 g/kg had a significant effect on growth performance, skin mucosal and serum antioxidant parameters, and the immune response (Giri et al. 2019). Additionally, *Ziziphus jujube* fruit extracts had significant effects on common carp fingerling growth and immunity (Hoseinifar et al. 2019). In a feeding experiment conducted to investigate the effects of dietary medlar (*Sami germanica*) leaf extracts on common carp, the herb had beneficial effects on growth performance and the immune system (Hoseinifar et al. 2017; Chen et al. 2017) reported that the active materials magnolol and honokiol from *Magnolia officinalis* had antiviral effects against grass carp reovirus.

The effects of applications of medicinal herbs as antiparasitic agents in freshwater aquaculture have been studied by many researchers. In goldfish (*Carassius auratus*) culture, exposure to neem (*Azadirachta indica*) leaves and magnolol from *M. officinalis* resulted in significant control of infection by *A. japonica* and *I. multifiliis in vitro* and *in vivo* (Kumari et al. 2019). Curcumin also showed antiparasitic activity against *I. multifiliis* (Liu et al. 2017). Dietary supplementation with medicinal plants or their active ingredients in snakehead fish (*Channa argus*) has been reported. Flavonoids are the active ingredients and have many health benefits. Addition of medicinal plant *Allium mongolicum regal* at 40 mg/kg to snakehead fish diet significantly improved growth performance, immune and antioxidant status, and disease resistance (Li et al. 2019a; Elabd et al. 2016) found that dietary supplementation with *Glycyrrhiza glabra* (liquorice) and *Astragalus membranaceus* promoted growth performance and the immune system, which suggested their role in natural antistress activity (Elabd et al. 2016). Dietary supplementation of *Piaractus mesopotamicus* with aloe vera provoked innate immune response, suggesting that it may help prevent pathogens outbreaks (Zanuzzo et al. 2017). The native Amazonian fish *Colossoma macropomum* Cuvier, 1818 (tambaqui) is an important aquaculture species in South America. Dietary supplementation of *C. macropomum* with essential oil of *Lippia origanoides* Kunth (Verbenaceae) and *M. piperita* had beneficial effects on fish health. *Lippia Kunth origanoides* (Verbenaceae) and peppermint essential oil were active against monogenoidean parasites (Ribeiro et al. 2018).

Benefits of medicinal herbs in crustacean culture

Several studies have demonstrated that the use of medicinal herbs in crustacean aquaculture has the significant impacts. Some medicinal herbs can serve as antiviral agents, growth promoters, immune boosters, and antibacterial agents. Generally, the use of medicinal plants in crustacean culture has focused on economically important species such as crustaceans and crabs. White shrimp, *Litopenaeus vannamei*, was exposed to rose seed (*Rhodomyrtus tomentosa myrtle*), a traditional Vietnamese herb, and examined for antibacterial activity against AHPND (Dang et al. 2019). *R. tomentosa* extract acted as an antibacterial agent in a dose-dependent manner and increased survival rate. Some studies have combined medicinal herbs and antibiotics. In a study conducted by Zhai and Li (2019), combination of oral enrofloxacin and San-Huang-San in *L. vannamei* enhanced nonspecific immunity and resistance after challenge with an AHPND-causing strain of *V. parahaemolyticus*. They also claimed that the concentration of enrofloxacin could be reduced when a better therapeutic effect was obtained. Palanikumar et al. (2018) investigated the dietary supplementation with Mexican prickly poppy *Argemone mexicana* extract in *L. vannamei* and found that the extract significantly suppressed WSSV and *V. harveyi* infection, and enhanced the immune system. Injection of *Gynura bicolor* extract at any dose demonstrated physiological homeostasis maintenance as well as increased immunity against *V. alginolyticus* infection in *L. vannamei* (Hsieh et al. 2013). In *Penaeus monodon* dietary supplementation with honeysuckle flowers of *Lonicera japonica* Thunb at 0.2-0.4% significantly enhanced growth parameters and survival (Chen et al. 2013). Other studies have reported that the dietary intake of Guava (*Psidium guajava* L.) leaf extracts increased the growth performance and nonspecific immune response of *P. monodon* (Yin et al. 2014). Dietary intake of *Agathi grandiflora* has been shown to increase activity against WSSV and enhance the immune system of *Fenneropenaeus indicus* (Bindhu et al. 2014). *Moringa oleifera* leaf extract at 0.5% has been reported to increase the growth performance, immune function as well as prevent fish stress of high ammonia exposure in the freshwater prawn, *Macrobachium rosenbergii* (Kaleo et al. 2019). Crayfish *Procambarus clarkia* was fed with *Gardenia jasminoides* to identify the antiviral activities against WSSV. The study demonstrated that *G. jasminoides* could modulate apoptosis-related factors and possessed antioxidative activity in crayfish. Moreover, *G. jasminoides* has been proved to inhibit WSSV replication and enhance survival rate of WSSV-challenged crayfish (Huang et al. 2019; Zheng et al. 2019) reported that the dietary supplementation with icariin at 100 mg/kg, the active ingredient of the herb *Epimedium grandiflorum*, was effective in enhancing growth parameters, antioxidant activity, and nonspecific immunity in the Chinese mitten crab (*Eriocheir sinensis*) (Zheng et al. 2019).

Conclusions and perspectives

Studies of the applications of medicinal herbs are generally carried out on various aquaculture species of high commercial value, such as marine fish (grouper, rainbow trout, and sea bream), freshwater fish (tilapia and carp), and crustaceans (shrimp). Medicinal herbs applied in marine, freshwater, and crustacean aquaculture have useful properties, including growth promotion; immune boosting; antiviral, antibacterial, and antiparasitic activities; and stress reduction. The differences in physiological and functional mechanisms of medicinal herbs in marine, freshwater, and crustacean aquaculture are interesting and require further exploration. Some herbs that have shown significant effects on fish growth also need further investigation because growth performance is one of the most important parameters in aquaculture. In addition, large-scale commercial production of medicinal herbs is an important consideration in tackling the problems facing the aquaculture industry. The combination of multi-omics approach (transcriptomics, epigenetics, metabolomics, metatranscriptomics for gut microbiota, and proteomics for host) and traditional immunological, physiological and pathological analysis can provide a better understanding of the molecular mechanism of medicinal herbs action, which will contribute to the effective application of medicinal herbs in aquaculture.

Funding This work was supported by grants from the National Natural Science Foundation of China (41966004; U20A20102), the Natural Science Foundation of Guangxi (2020GXNSFBA297161; AD19245022), Guangxi Innovation Team Project of National Modern Agricultural Industrial Technology System (nycytxgx-cxtd-2021-08-02), and the Basic Research Fund of Guangxi Academy of Sciences (2018YJJ903; 2019YJJ1005; 2018YJJ902).

Data availability Public available data.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare no conflict of interest.

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