Ann. Anim. Sci., Vol. 23, No. 4 (2023) 971–977 *DOI: 10.2478/aoas-2023-0007*

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A MINI-REVIEW ON PLANT-DERIVED PHENOLIC COMPOUNDS WITH PARTICULAR EMPHASIS ON THEIR POSSIBLE APPLICATIONS AND BENEFICIAL USES IN AQUACULTURE

Mohammed A.E. Naiel[1], Abdullah I. El-Kholy[2], Samar S. Negm[3], Shakira Ghazanfar[4], Mustafa Shukry[5], Zhaowei Zhang[6], Ehsan Ahmadifar[7], Hany M.R. Abdel-Latif[8]♦

[1]Department of Animal Production, Faculty of Agriculture, Zagazig University, Zagazig 44519, Egypt
[2]Pharmaceutical Technology Unit, National Institute of Laser Enhanced Sciences, Cairo University, Giza 12613, Egypt
[3]Fish Biology and Ecology Department, Central Lab for Aquaculture Research, Abbassa, Agriculture Research Center, Giza 12619, Egypt
[4]National Institute for Genomics Advanced and Biotechnology (NIGAB), National Agricultural Research Centre, Park Road, Islamabad 45500, Pakistan
[5]Physiology Department, Faculty of Veterinary Medicine, Kafrelsheikh University, Kafrelsheikh *33516*, Egypt
[6]National Reference Laboratory for Agricultural Testing (Biotoxin), Key Laboratory of Biology and Genetic Improvement of Oil Crops, Key Laboratory of Detection for Mycotoxins, Ministry of Agriculture and Rural Affairs, Oil Crops Research Institute of Chinese Academy of Agricultural Sciences, Wuhan 430062, PR China
[7]Department of Fisheries, Faculty of Natural Resources, University of Zabol, Zabol 98615-538, Iran
[8]Department of Poultry and Fish Diseases, Faculty of Veterinary Medicine, Alexandria University, Alexandria 22758, Egypt
♦Corresponding author: hmhany@alexu.edu.eg

Abstract

The use of most antibiotics has been restricted and banned in finfish and shrimp farms due to several reasons comprising their long-lasting persistence in aquatic environments, relatively high prices, and their ability to promote the existence of antibiotic-resistant bacteria. Hence, finding economical, natural, and environmentally safe alternatives is of great importance. The use of polyphenols, polyphenol-rich plants, and plant-derived phenolic compounds for promoting aquatic animal health and welfare could be from the effective strategies for developing aquafeed and maintaining the sustainability of the aquaculture industry. Several plants are gorgeous in various bioactive functional ingredients known as phytochemicals and polyphenols. Phenolic compounds could be successfully used as natural immunostimulants in order to raise the immunity of finfish and shrimp species against several bacterial, viral, and parasitic infections and thus may replace the use of antimicrobial agents. Besides their potential roles for improvement of the growth performance, intestinal health, and enhancing the antioxidant capacity of the treated animals. Even though the trend of using plant-derived phenolic compounds is a new and leading era for the improvement of the functionality of aquafeed and the development of the aquaculture industry, there are fundamental needs and necessities to describe a clear understanding of their modes of action and potential roles in the improvement of the production rates, antioxidant activity, immune status, and disease resistance of farmed fish and shrimp.

Key words: phenolics, phytochemicals, disease resistance, antioxidants, polyphenols

In aquaculture, fish rearing under intensive stocking densities usually induces stressful effects and encourages the spreading of infectious pathogens such as bacteria, fungi, viruses, and parasites among the fish population (Abdel-Latif and Khafaga, 2020; El-Son et al., 2021). The emergence of bacterial, viral, parasitic, fungal, and protozoal diseases of fish will cause high mortalities, decreased production rates, and relatively high economic loss, which nearly accounts for six billion dollars in revenue loss per year (Assefa and Abunna, 2018). On the other hand, the fish immune system may not be able to counteract the negative consequences of these infections, particularly when co-infections flourish simultaneously (Abdel-Latif et al., 2020). In this case, the use of antibiotics in fish diets or the rearing water has been considered the most common interference by the veterinarians or aquaculturists to prevent and/or control infectious diseases and reduce the mortalities and kills that may occur in fish farms as a result of the emerging diseases (Cabello, 2006; Vincent et al., 2019). However, using high amounts of antibiotics might encourage the development of antibiotic-resistant bacteria and increase environmental risks (Alderman and Hastings, 1998; Santos and Ramos, 2018). Hence, there is an urgent need to find alternatives to replace antibiotic use in aquaculture (Defoirdt et al., 2011).

During the last decade, medicinal plants and their extracts have been extensively used as an alternative to antibiotics and immunostimulants in fish farming (Vaseeharan and Thaya, 2014). Plants have numerous beneficial applications in aquaculture because of their anti-stress, antibacterial, growth-promoting, appetite-stimulating, and immunostimulatory effects (Naiel et al., 2019; Abd El-Naby et al., 2020; Naiel et al., 2020; Li et al., 2022).

Medicinal plants also have the potential ability to enhance antioxidant responses and increase fish resistance to bacterial, viral, and parasite diseases (Shekarabi et al., 2022 a, b). A wide range of plants and their extracts can be efficiently used as dietary supplements, such as *Moringa oleifera* (Abdel-Latif et al., 2022 a; El-Son et al., 2022; Mahmoud et al., 2022), *Silybum marianum* (Abdel-Latif et al., 2023), *Ginkgo biloba* (Abdel-Latif et al., 2021), *Astragalus membranaceus* (Farag et al., 2021, 2022; Abdel-Latif et al., 2022 b), *Origanum vulgare*, *Hypericum perforatum*, and *Melissa officinalis* (Mohammadi et al., 2020), date palm (*Phoenix dactylifera*) (Mohammadi et al., 2018), dandelion (*Taraxacum officinale*) (Mostafavi et al., 2022), *Berberis vulgaris* fruit extract (Ramezani et al., 2021), and *Citrus paradisi* peel extract (Samavat et al., 2019). The benefits and applications of their functional bioactive compounds (phytochemicals) have also been reported (Chakraborty and Hancz, 2011; Chakraborty et al., 2014). Phenolic acids and polyphenols are the most studied phytochemicals since they were proven to effectively promote the overall health status of fish (Dawood et al., 2020; Hoseinifar et al., 2020; Ahmadifar et al., 2021; Naiel et al., 2021). The beneficial effects of the plant-derived phenolic compounds may be linked to their effectiveness in enhancing the immune system and raising fish resistance against challenging infectious agents (Wang et al., 2018). Taken together, this review article aims to give an overview and insight into plant-derived phenolic compounds and spotlights their beneficial effects and potential possible applications in aquaculture.

Plant-derived phenolic compounds

The term "phytochemicals" refers to the non-nutritive chemical compounds produced by plants since the plant kingdom is the major source of such compounds (Chakraborty and Hancz, 2011; Chakraborty et al., 2014; Ahmadifar et al., 2021). Phenols or plant-derived phenolic compounds are a group of phytochemicals that are characterized by the presence of one or more phenolic groups. Chemically, a phenol contains at least one benzene ring substituted with at least one hydroxyl group. The simplest member of this category is phenol or monohydroxy benzene. Phenols are an expanded category of several organic compounds widely used in several fields, such as medicine, pharmacy, agriculture, and the polymer industry. Plants are the primary source of phenols, which are secondary metabolites (plant byproducts) performing vital roles in plant development, biosynthesis, ultraviolet radiation protection, and defense mechanisms (Pandey and Rizvi, 2009; Bhattacharya et al., 2010). Phenols of plant origin (or what is known as phytophenols) may be monocyclic (such as catechol and resorcinol) or polycyclic (polyphenols) (such as resveratrol, curcumin, delphinidin, and quercetin) (Dormán et al., 2021; Maiti and Dunbar, 2018; Salehi et al., 2018). Plant phenols can be classified according to the degree of complexity into five basic classes: monomeric, dimeric, oligomeric, polymeric, and hybrid phenols. Each class is further subdivided into subclasses according to the number of benzene rings and the attached carbon atoms. From the phenol classes, it was found that monomeric phenols represent the most common and abundant phenolics in plants, covering a wide variety of derivative compounds, such as benzoic acid, benzaldehyde, hydroxycinnamic acids, cinnamic aldehyde, coumarins, isocoumarins, chromones, xanthonoids, stilbenoids, anthraquinones, anthrones, diarylheptanoids and flavonoids (Tsimogiannis and Oreopoulou, 2019). It is noteworthy that coumarin and isocoumarin are not phenols, but their 6-, 7-, 8-, and 9-hydroxy derivatives are considered phenols. Similarly, benzoic acid, benzaldehyde, and cinnamic acids are not phenols, but their hydroxy-benzene derivatives are so. Being mainly composed of more than one phenolic ring and due to the relative rareness of plant-derived monocyclic phenols (Tsimogiannis and Oreopoulou, 2019), "polyphenols" terminology may be generalized to describe phytophenols.

Sources of plant-derived phenolics

Plant sources of phytophenols vary widely from marine algae to higher plants (Li et al., 2014). For instance, *Jania rubens*, *Corallina mediterranea,* and *Pterocladia capillacea* are red algal species containing various levels of phytophenols such as flavonoids (Mohy El-Din and El-Ahwany, 2016). Phytophenols could also be extracted from a wide variety of higher plants, such as daily consumed cereals, vegetables, and fruits (Maqsood et al., 2014; Mileo et al., 2019; Ahmadifar et al., 2021). Besides, agro-industrial wastes represent an eco-friendly source for phytophenols since these products contain high amounts of these compounds, which could be extracted and recycled in an eco-friendly manner minimizing the harmful environmental effects (Leyva-López et al., 2020).

Benefits of plant-derived phenolics and their possible application in aquaculture

Using phenolic compounds represents multi-purpose feed supplements for improving the aquaculture industry, especially in controlling and preventing diseases, and is also considered a safe option, especially when compared with antibiotics and other antimicrobials. Because of their unique benefits and functions, these phytochemicals may benefit several aspects of the aquaculture industry, such as immunostimulant, antioxidant, antibacterial, antiviral, antifungal, and antiprotozoal agents.

Immunostimulatory roles

The immunostimulatory effects of phytophenols are well-documented in human and various animal research (John et al., 2011; Yahfoufi et al., 2018; Mileo et al., 2019). Studies reported several immunomodulatory mechanisms of phytophenols regarding the targeting of cellular receptors (e.g., epigallocatechin gallate), the induction of the regulatory T-cells (e.g., naringin), and of

the apoptotic cell death (e.g., resveratrol), the regulation of innate and adaptive immune response (e.g., baicalin) and the activation of immune-related gene expression (Ding et al., 2018). In fish studies, there are several modes of action of phytophenols. For example, it was found that feeding European sea bass (*Dicentrarchus labrax*) with phytophenols-enriched diets (red grape extract) significantly modulated the intestinal and spleen immune responses, resulting in an improvement of the immunity and overall health status (Magrone et al., 2016). Similarly, the dietary administration of *Chenopodium ambrosioides* extracts enhanced the immunological response in the Pacific red snapper (*Lutjanus peru*) (Maldonado-Garcia et al., 2019). However, a detailed description of the actual immunomodulatory effects of phytophenols, particularly on expression analysis of immune-related genes in immune organs and enhancing disease resistance in fish and shrimp, still requires further investigation.

Antioxidant roles

Generally, the primary roles of antioxidants are to reduce or counteract oxidative stress by quenching free radicals or chelating redox metals (Ayyat et al., 2020). Antioxidants may be relatively small molecules known as low molecular weight antioxidants, such as ascorbic acid, lipoic acid, polyphenols, and vitamin E or macromolecules, e.g., enzymes. This is mainly related to the hydroxyl groups, which play a crucial role in the antioxidant actions of phytophenols as radical scavengers and metal ions chelators (Hussain et al., 2016). Phytophenols significantly help to overcome such a problem through their potent antioxidant properties. For example, purple coneflower (*Echinacea purpurea*) polyphenols were reported to have antioxidant effects when added as a nutritional supplement in the feeding regime, protecting fish from oxidative stress-related diseases (Oniszczuk et al., 2019). These polyphenols include caftaric acid, chlorogenic acid, echinacoside, cynarin, and cichoric acid, among others (Oniszczuk et al., 2019). Similarly, tea polyphenols supplementation also reduced the effects of high lipid diet-induced lipid oxidation and oxidative stress in the large yellow croaker (*Larimichthys crocea*) (Ji et al., 2018). As a result, plant-derived polyphenols represent a potent, safe, and eco-friendly option to protect fish from the harmful consequences of oxidative stress (Dai and Mumper, 2010).

Antibacterial activities

The most common fish pathogenic bacteria include *Vibrio* and *Flavobacterium* species (Sudheesh et al., 2012), *Edwardsiella* and *Aeromonas* species (Prasad et al., 2014), and *Streptococcus* species (Baiano and Barnes, 2009) among several others (Austin, 2011). On the other hand, the extensive use of antibiotics in aquaculture represents a serious threat to the farmed fish or shrimp with the possibility of the emergence of antibiotic-resistant bacteria (Watts et al., 2017). The introduction of plant phenols as antibacterial agents in aquaculture has been recently approved as an alternative option with potential effectiveness and a wide safety margin. Table 1 briefly illustrates the plant sources, phenolic compounds, and their possible antibacterial activities against bacterial agents. It was found that synergistic antibacterial effects were reported between polyphenolics in *Cistus salviifolius* extract (Aldulaimi, 2017). Similarly, a combination of gallic acid and quercetin produced synergistic antibacterial activities against *Aeromonas salmonicida*, *Aeromonas hydrophila,* and *Edwardsiella tarda* (Prasad et al., 2014). This may open the field toward incorporating many plant-derived phenolic combinations whose strengths may surpass the use of traditional antibiotics (Kot et al., 2019). Being of plant origin, phytophenols can also be introduced in aquaculture feeding systems in raw form (i.e., the whole plant part) rather than in the form of extracts, taking into consideration other possible active ingredients that may be present. Programmed cultivation of phenolics-rich plants may represent a more practical solution, saving time and cost.

Table 1. The antibacterial activities of some plant-derived phenolic compounds against some bacterial infections

Phenolic compounds	Plant sources	Antibacterial actions	References
Caffeic acid	Coffee, blueberries, and apples	*Staphylococcus aureus* *E. coli*	Pietta et al., 2003
Gallic acid	Blueberries, plums, blackberry, strawberry, grapes, cashew nut, hazelnut, walnut, and tea	*E. coli*	Kang et al., 2018
Phenolic compounds	*Rhus verniciflua*	*Edwardsiella tarda* *Vibrio anguillarum* *Streptococcus iniae*	Jang et al., 2018
Methyl gallate	*Galla rhois*	*Salmonella* strains	Choi et al., 2009
Epigallocatechin, punicalagin, castalagin, prodelphinidin, geraniin and procyanidins	Cocoa (*Theobroma cacao*) and grapes	*Staphylococcus aureus*	Taguri et al., 2004
Tannic acid, gallic acid, and propyl gallate	Wide variety of grains and fruits	*Cytophaga columnaris*	Zhao et al., 1997
Cranberry A-type proanthocyanidins	Cranberry (*Vaccinium macrocarpon)*	*E. coli*	Howell et al., 2005

Antiviral activities

Viral diseases are usually associated with heavy losses in aquaculture, affecting a wide variety of farmed fish, and are considered significant limiting factors in the expansion of aquaculture (Ahne, 1994). Viral diseases in aquaculture are caused by several families of viral agents, such as Birnaviridae (e.g., aquabirnavirus and infectious pancreatic necrosis virus), Togaviridae (e.g., salmonid alphavirus), Nodaviridae (e.g., nervous necrosis virus and betanodavirus), Rhabdoviridae (e.g., epizootic hematopoietic necrosis virus, infectious hematopoietic necrosis virus and viral hemorrhagic septicemia virus), Orthomyxoviridae (e.g., infectious salmon anemia virus) (Crane and Hyatt, 2011; Munang'andu et al., 2016) among several others. Notably, viral outbreaks in fish farms may cause a mortality rate of up to 100% (Crane and Hyatt, 2011). Moreover, prevention and control strategies using biosecurity measures, selective breeding for disease resistance strains, and vaccination are essential and may provide solutions depending on the type and degree of viral infection (Munang'andu et al., 2016). Few compounds were reported to be effective as preventive and/or therapeutic antivirals in aquaculture, such as LJ001, which is a broad-spectrum antiviral acting against enveloped viruses, and JL122, which is a broad-spectrum antiviral inhibiting transmission of aquatic rhabdoviruses (Balmer et al., 2017, 2018). Despite the promising results of these two compounds, their antiviral action is limited to enveloped viruses and to the fact that both are light activated, thus creating possible practical concerns regarding their potential application. Additionally, these compounds were not applied to large populations, lacking feedback about their possible side effects or toxicity. Few studies on the antiviral roles of plant-derived phenolics were reported. For example, studies showed that pomegranate bioactive polyphenols ellagitannins exerted antiviral activities (Hikal et al., 2022). Another study revealed the antiviral activity of oligonol, a polyphenol extracted from Lychee tree (*Litchi chinensis*) (Kilari and Putta, 2016). Therefore, using plant phenolics to prevent and control viral infections in aquaculture remains of limited outcomes and should be considered as a part of future research strategies.

Antifungal activities

Fungal infections are well-known to cause fish diseases and usually result from ecological stress, poor water quality, general immunosuppression, or injury of the fish exterior surfaces, where fungi become secondary or opportunistic invaders and, in this case, they can exaggerate the infection and disease signs (Yanong, 2003). The most common fish fungal infection is often associated with the members of the family *Saprolegniaceae* in the class Oomycetes or water molds (Khoo, 2000). Phytophenols can be utilized in prevention and prophylaxis against fungal infections in two ways: (a) directly acting as antifungal agents to early prevent or control the outbreak and (b) indirectly acting by enhancing immunological response and health status of aquatic animals (Salehi et al., 2016). Table 2 highlights the potential of several phytophenols obtained from natural sources that have proven powerful antifungal effects against several fungal infections. Although the studies mentioned in Table 2 declared that several phytophenols were reported to possess antifungal activities, rare information is available concerning their effects against fish diseases-causing fungi. This information requires detailed experimental *in vivo* and *in vitro* studies to illustrate correctly which one of the phytophenols could effectively control fish fungal infections.

Antiprotozoal activities

Protozoal parasites are pathogenic to freshwater and marine fish and may cause severe morbidity and mortality among farmed fish. The most common protozoan infections in fish are often caused by amoebae, flagellates, apicomplexans, microsporidians, and ciliates (Buchmann, 2013). Synthetic drugs antiprotozoal agents such as metronidazole and dimetridazole may be used to control protozoal infections, especially in aquarium-reared ornamental fish. Several phytophenols were reported to have beneficial effects in preventing protozoal diseases that may infect fish (Table 3). An earlier study showed that several polyphenols such as resveratrol, mangiferin, and (–)-epigallocatechin-3-gallate induced significantly *in vitro* antiparasitic effects against *Philasterides dicentrarchi* in turbot (*Scophthalmus maximus*) (Leiro et al., 2004). Moreover, it was reported that Psoralidin isolated from *Psoralea corylifolia* could effectively control the ciliated protozoan parasite *Ichthyophthirius multifiliis* in goldfish (*Carassius auratus*) (Song et al., 2015). In the same sense, it was reported that curcumin isolated from *Curcuma longa* induced antiparasitic effects against *I. multifiliis* in grass carp (*Ctenopharyngodon idella*) (Liu et al., 2017).

Table 2. The antifungal activities of some plant-derived phenolic compounds against some fungal infections

Polyphenolic compounds	Plant sources	Antifungal activities	References
Gallic acid	Pomegranate rind (*Punica granatum*)	*Candida albicans* *Trichophyton rubrum*	Li et al., 2017
Phenolics and polyphenols	Extracted from the resinous shrubs of *Escallonia illinita* by-products	*Saprolegnia* strains such as *S. parasitica* and *S. australis*	Montenegro et al., 2019
Eugenol	Extracted from flower buds of clove (*Syzygium aromaticum*)	*Saprolegnia* species (*S. parasitica, S. diclina, S. ferax*, and *S. salmonis*) *Achlya klebsiana* *Aphanomyces piscicida*	Hussein et al., 2000

Table 3. The antiprotozoal activities of some plant-derived phenolic compounds against some fish protozoan parasites

Phenolic compounds	Plant sources	Fish species	Antiprotozoal effects	References
Psoralidin	*Psoralea corylifolia*	Goldfish (*Carassius auratus*)	*Ichthyophthirius multifiliis*	Song et al., 2015
(–)-epigallocatechin-3-gallate	*Camellia sinensis*	Turbot (*Scophthalmus maximus*)	*Philasterides dicentrarchi*	Leiro et al., 2004
Resveratrol	Red grapes (*Vitis vinifera*)			
Mangiferin	*Mangifera indica*			
Curcumin	*Curcuma longa*	Grass carp (*Ctenopharyngodon idella*)	*Ichthyophthirius multifiliis*	Liu et al., 2017

Conclusions and perspectives

To put it briefly, plant-derived phenolic compounds have gained significant attention in recent years due to their benefits and applications in aquaculture. Previously published studies have shown the ability of these beneficial compounds to improve the growth performance and boost the antioxidant capacity of fish. Besides their roles in enhancing the immune responses and disease resistance to various fish diseases, thus, this may be considered a valid alternative for antibiotic usage. For the perspectives and future perceptions, it is necessary to study the modes of action of these natural supplements to promote their use in the aquaculture industry. Moreover, it is necessary to understand the mechanisms by which these phytochemicals work together at tissue and molecular levels.

Author contribution

All authors contributed equally to the conceptualization and writing the original draft of this article. All authors have read and approved the final manuscript.

Consent for publication

The authors approve processing this manuscript for publication.

Conflict of interest

None.

References

Abd El-Naby A.S., Al-Sagheer A.A., Negm S. S., Naiel M.A.E. (2020). Dietary combination of chitosan nanoparticle and thymol affects feed utilization, digestive enzymes, antioxidant status, and intestinal morphology of *Oreochromis niloticus*. Aquaculture, 515: 734577.

Abdel-Latif H.M.R., Khafaga A.F. (2020). Natural co-infection of cultured Nile tilapia *Oreochromis niloticus* with *Aeromonas hydrophila* and *Gyrodactylus cichlidarum* experiencing high mortality during summer. Aquac. Res., 51: 1880–1892.

Abdel-Latif H.M.R., Dawood M.A.O., Menanteau-Ledouble S., El-Matbouli M. (2020). The nature and consequences of co-infections in tilapia: A review. J. Fish Dis., 43: 651–664.

Abdel-Latif H.M.R., Hendam B.M., Nofal M.I., El-Son M.A.M. (2021). *Ginkgo biloba* leaf extract improves growth, intestinal histomorphometry, immunity, antioxidant status and modulates transcription of cytokine genes in hapa-reared *Oreochromis niloticus*. Fish Shellfish Immunol., 117: 339–349.

Abdel-Latif H.M.R., Abdel-Daim M.M., Shukry M., Nowosad J., Kucharczyk D. (2022 a). Benefits and applications of *Moringa oleifera* as a plant protein source in aquafeed: A review. Aquaculture, 547: 737369.

Abdel-Latif H.M.R., Ahmed H.A., Shukry M., Chaklader M.R., Saleh R.M., Khallaf M.A. (2022 b). *Astragalus membranaceus* extract (AME) enhances growth, digestive enzymes, antioxidant capacity, and immunity of *Pangasianodon hypophthalmus* juveniles. Fishes, 7: 319.

Abdel-Latif H.M.R., Shukry M., Noreldin A.E., Ahmed H.A., El-Bahrawy A., Ghetas H.A., Khalifa E. (2023). Milk thistle (*Silybum marianum*) extract improves growth, immunity, serum biochemical indices, antioxidant state, hepatic histoarchitecture, and intestinal histomorphometry of striped catfish, *Pangasianodon hypophthalmus*. Aquaculture, 562: 738761.

Ahmadifar E., Yousefi M., Karimi M., Fadaei Raieni R., Dadar M., Yilmaz S., Dawood M.A.O., Abdel-Latif H.M.R. (2021). Benefits of dietary polyphenols and polyphenol-rich additives to aquatic animal health: An overview. Rev. Fish. Sci. Aquac., 29: 478–511.

Ahne W. (1994). Viral infections of aquatic animals with special reference to Asian aquaculture. Annu. Rev. Fish Dis., 4: 375–388.

Alderman D.J., Hastings T.S. (1998). Antibiotic use in aquaculture: development of antibiotic resistance – potential for consumer health risks. Int. J. Food Sci. Technol., 33: 139–155.

Aldulaimi O.A. (2017). General overview of phenolics from plant to laboratory, good antibacterials or not. Pharmacogn. Rev., 11: 123–127.

Assefa A., Abunna F. (2018). Maintenance of fish health in aquaculture: Review of epidemiological approaches for prevention and control of infectious disease of fish. Vet. Med. Int., 5432497.

Austin B. (2011). Taxonomy of bacterial fish pathogens. Vet. Res., 42: 20.

Ayyat M.S., Ayyat A.M.N., Naiel M.A.E., Al-Sagheer A.A. (2020). Reversal effects of some safe dietary supplements on lead contaminated diet induced impaired growth and associated parameters in Nile tilapia. Aquaculture, 515: 734580.

Baiano J.C., Barnes A.C. (2009). Towards control of *Streptococcus iniae*. Emerg. Infect. Dis., 15: 1891–1896.

Balmer B.F., Powers R.L., Zhang T.H., Lee J., Vigant F., Lee B., Jung M.E., Purcell M.K., Snekvik K., Aguilar H.C. (2017). Inhibition of an aquatic rhabdovirus demonstrates promise of a broad-spectrum antiviral for use in aquaculture. J. Virol., 91: e02181-16.

Balmer B.F., Getchell R.G., Powers R.L., Lee J., Zhang T., Jung M.E., Purcell M.K., Snekvik K., Aguilar H.C. (2018). Broad-spectrum antiviral JL122 blocks infection and inhibits transmission of aquatic rhabdoviruses. Virology, 525: 143–149.

Bhattacharya A., Sood P., Citovsky V. (2010). The roles of plant phenolics in defence and communication during *Agrobacterium* and *Rhizobium* infection. Mol. Plant Pathol., 11: 705–719.

Buchmann K. (2013). Impact and control of protozoan parasites in maricultured fishes. Parasitology, 142: 168–177.

Cabello F.C. (2006). Heavy use of prophylactic antibiotics in aquaculture: a growing problem for human and animal health and for the environment. Environ. Microbiol., 8: 1137–1144.

Chakraborty S.B., Hancz C. (2011). Application of phytochemicals as immunostimulant, antipathogenic and antistress agents in finfish culture. Rev. Aquac., 3: 103–119.

Chakraborty S.B., Horn P., Hancz C. (2014). Application of phytochemicals as growth-promoters and endocrine modulators in fish culture. Rev. Aquac., 6: 1–19.

Choi J.-G., Kang O.-H., Lee Y.-S., Oh Y.-C., Chae H.-S., Jang H.-J.,

Shin D.-W., Kwon D.-Y. (2009). Antibacterial activity of methyl gallate isolated from *Galla rhois* or carvacrol combined with nalidixic acid against nalidixic acid resistant bacteria. Molecules, 14: 1773–1780.

Crane M., Hyatt A. (2011). Viruses of fish: An overview of significant pathogens. Viruses, 3: 2025–2046.

Dai J., Mumper R.J. (2010). Plant phenolics: Extraction, analysis and their antioxidant and anticancer properties. Molecules, 15: 7313–7352.

Dawood M.A.O., Metwally A.E.-S., El-Sharawy M.E., Ghozlan A.M., Abdel-Latif H.M.R., Van Doan H., Ali M.A.M. (2020). The influences of ferulic acid on the growth performance, haemato-immunological responses, and immune-related genes of Nile tilapia (*Oreochromis niloticus*) exposed to heat stress. Aquaculture, 525: 735320.

Defoirdt T., Sorgeloos P., Bossier P. (2011). Alternatives to antibiotics for the control of bacterial disease in aquaculture. Curr. Opin. Microbiol., 14: 251–258.

Ding S., Jiang H., Fang J. (2018). Regulation of immune function by polyphenols. J. Immunol. Res., 1264074.

Dormán G., Flachner B., Hajdú I., András C. (2021). Chapter 23 – Target identification and polypharmacology of nutraceuticals. In: Nutraceuticals, Gupta R.C., Lall R., Srivastava A. (eds). 2nd edition. Academic Press, pp. 315–343.

El-Son M.A.M., Nofal M.I., Abdel-Latif H.M.R. (2021). Co-infection of *Aeromonas hydrophila* and *Vibrio parahaemolyticus* isolated from diseased farmed striped mullet (*Mugil cephalus*) in Manzala, Egypt – A case report. Aquaculture, 530: 735738.

El-Son M.A.M., Hendam B.M., Nofal M.I., Abdel-Latif H.M.R. (2022). Effects of *Moringa oleifera*-based diets on growth, immunological responses, liver antioxidant biomarkers and expression of immune-related genes in Nile tilapia (*Oreochromis niloticus*) raised in hapa-in-pond system. Aquac. Res., 53: 4338–4352.

Farag M.R., Alagawany M., Khalil S.R., Moustafa A.A., Mahmoud H.K., Abdel-Latif H.M.R. (2021). *Astragalus membranaceus* polysaccharides modulate growth, hemato-biochemical indices, hepatic antioxidants, and expression of *HSP70* and apoptosis-related genes in *Oreochromis niloticus* exposed to sub-lethal thallium toxicity. Fish Shellfish Immunol., 118: 251–260.

Farag M.R., Alagawany M., Khalil S.R., El-Hady E.W., Elhady W.M., Ismail T.A., Marini C., Di Cerbo A., Abdel-Latif H.M.R. (2022). Immunosuppressive effects of thallium toxicity in Nile tilapia fingerlings: Elucidating the rescue role of *Astragalus membranaceus* polysaccharides. Front. Vet. Sci., 9: 843031.

Hikal W., Said-Al Ahl H., Tkachenko K., Mahmoud A., Bratovcic A., Hodžić S., Atanassova M. (2022). An overview of pomegranate peel: A waste treasure for antiviral activity. Trop. J. Nat. Prod. Res., 6: 15–19.

Hoseinifar S.H., Jahazi M.A., Nikdehghan N., Van Doan H., Volpe M.G., Paolucci M. (2020). Effects of dietary polyphenols from agricultural by-products on mucosal and humoral immune and antioxidant responses of convict cichlid (*Amatitlania nigrofasciata*). Aquaculture, 517: 734790.

Howell A.B., Reed J.D., Krueger C.G., Winterbottom R., Cunningham D.G., Leahy M. (2005). A-type cranberry proanthocyanidins and uropathogenic bacterial anti-adhesion activity. Phytochemistry, 66: 2281–2291.

Hussain T., Tan B., Yin Y., Blachier F., Tossou M.C.B., Rahu N. (2016). Oxidative stress and inflammation: What polyphenols can do for us? Oxid. Med. Cell. Longev., 7432797.

Hussein M.M.A., Wada S., Hatai K., Yamamoto A. (2000). Antimycotic activity of eugenol against selected water molds. J. Aquat. Anim. Health, 12: 224–229.

Jang J.Y., Shin H., Lim J.-W., Ahn J.H., Jo Y.H., Lee K.Y., Hwang B.Y., Jung S.-J., Kang S.Y., Lee M.K. (2018). Comparison of antibacterial activity and phenolic constituents of bark, lignum, leaves and fruit of *Rhus verniciflua*. PLOS ONE, 13: e0200257.

Ji R., Li Y., Li X., Xiang X., Li Y., Zhu S., Yang B., Zhang Y., Mai K., Ai Q. (2018). Effects of dietary tea polyphenols on growth, biochemical and antioxidant responses, fatty acid composition and expression of lipid metabolism related genes of large yellow croaker (*Larimichthys crocea*). Aquac. Res., 49: 1210–1218.

John C.M., Sandrasaigaran P., Tong C.K., Adam A., Ramasamy R. (2011). Immunomodulatory activity of polyphenols derived from *Cassia auriculata* flowers in aged rats. Cell. Immunol., 271: 474–479.

Kang J., Li Q., Liu L., Jin W., Wang J., Sun Y. (2018). The specific effect of gallic acid on *Escherichia coli* biofilm formation by regulating pgaABCD genes expression. Appl. Microbiol. Biotechnol., 102: 1837–1846.

Khoo L. (2000). Fungal diseases in fish. Seminars in Avian and Exotic Pet Medicine, 9: 102–111.

Kilari E.K., Putta S. (2016). Biological and phytopharmacological descriptions of *Litchi chinensis*. Pharmacogn. Rev., 10: 60–65.

Kot B., Kwiatek K., Janiuk J., Witeska M., Pękala-Safińska A. (2019). Antibacterial activity of commercial phytochemicals against *Aeromonas* species isolated from fish. Pathogens, 8: 142.

Leiro J., Arranz J.A., Parama A., Alvarez M.F., Sanmartin M.L. (2004). *In vitro* effects of the polyphenols resveratrol, mangiferin and (–)-epigallocatechin-3-gallate on the scuticociliate fish pathogen *Philasterides dicentrarchi*. Dis. Aquat. Org., 59: 171–174.

Leyva-López N., Lizárraga-Velázquez C.E., Hernández C., Sánchez-Gutiérrez E.Y. (2020). Exploitation of agro-industrial waste as potential source of bioactive compounds for Aquaculture. Foods, 9: 843.

Li A.-N., Li S., Zhang Y.-J., Xu X.-R., Chen Y.-M., Li H.-B. (2014). Resources and biological activities of natural polyphenols. Nutrients, 6: 6020–6047.

Li M., Wei D., Huang S., Huang L., Xu F., Yu Q., Liu M., Li P. (2022). Medicinal herbs and phytochemicals to combat pathogens in aquaculture. Aquac. Int., 30: 1239–1259.

Li Z.-J., Liu M., Dawuti G., Dou Q., Ma Y., Liu H.-G., Aibai S. (2017). Antifungal activity of gallic acid *in vitro* and *in vivo*. Phytother. Res., 31: 1039–1045.

Liu Y.-M., Zhang Q.-Z., Xu D.-H., Fu Y.-W., Lin D.-J., Zhou S.-Y., Li J.-P. (2017). Antiparasitic efficacy of curcumin from *Curcuma longa* against *Ichthyophthirius multifiliis* in grass carp. Vet. Parasitol., 236: 128–136.

Magrone T., Fontana S., Laforgia F., Dragone T., Jirillo E., Passantino L. (2016). Administration of a polyphenol-enriched feed to farmed sea bass (*Dicentrarchus labrax* L.) modulates intestinal and spleen immune responses. Oxid. Med. Cell. Longev., 2827567.

Mahmoud H.K., Farag M.R., Reda F.M., Alagawany M., Abdel-Latif H.M.R. (2022). Dietary supplementation with *Moringa oleifera* leaves extract reduces the impacts of sub-lethal fipronil in Nile tilapia, *Oreochromis niloticus*. Sci. Rep., 12: 21748.

Maiti P., Dunbar G.L. (2018). Use of curcumin, a natural polyphenol for targeting molecular pathways in treating age-related neurodegenerative diseases. Int. J. Mol. Sci., 19: 1637.

Maldonado-Garcia M., Angulo C., Vazquez-Martinez J., Sanchez V., Lopez M.G., Reyes-Becerril M. (2019). Antioxidant and immunostimulant potentials of *Chenopodium ambrosioides* L. in Pacific red snapper (*Lutjanus peru*). Aquaculture, 513: 734414.

Maqsood S., Benjakul S., Abushelaibi A., Alam A. (2014). Phenolic compounds and plant phenolic extracts as natural antioxidants in prevention of lipid oxidation in seafood: A detailed review. Compr. Rev. Food Sci. Food Saf., 13: 1125–1140.

Mileo A.M., Nisticò P., Miccadei S. (2019). Polyphenols: Immunomodulatory and therapeutic implication in colorectal cancer. Front. Immunol., 10.

Mohammadi G., Rafiee G., El Basuini M.F., Van Doan H., Ahmed H.A., Dawood M.A.O., Abdel-Latif H.M.R. (2020). Oregano (*Origanum vulgare*), St John's-wort (*Hypericum perforatum*), and lemon balm (*Melissa officinalis*) extracts improved the growth rate, antioxidative, and immunological responses in Nile tilapia (*Oreochromis niloticus*) infected with *Aeromonas hydrophila*. Aquac. Rep., 18: 100445.

Mohammadi M., Soltani M., Siahpoosh A., Hosseini Shekarabi S.P., Shamsaie Mehrgan M., Lymbery A. (2018). Effect of date palm (*Phoenix dactylifera*) seed extract as a dietary supplementation on growth performance immunological haematological biochemical parameters of common carp. Aquac. Res., 49: 2903–2912.

Mohy El-Din S.M., El-Ahwany A.M.D. (2016). Bioactivity and phytochemical constituents of marine red seaweeds (*Jania rubens*, *Cor-*

allina mediterranea and *Pterocladia capillacea*). J. Taibah Univ. Sci., 10: 471–484.

Montenegro I., Sánchez E., Werner E., Godoy P., Olguín Y., Caro N., Ehrenfeld N., Madrid A. (2019). Isolation and identification of compounds from the resinous exudate of *Escallonia illinita* Presl. and their anti-oomycete activity. BMC Chemistry, 13: 1.

Mostafavi Z.S., Shekarabi S.P.H., Mehrgan M.S., Islami H.R. (2022). Amelioration of growth performance, physio-metabolic responses, and antioxidant defense system in rainbow trout, *Oncorhynchus mykiss*, using dietary dandelion, *Taraxacum officinale*, flower extract. Aquaculture, 546: 737296.

Munang'andu H.M., Mutoloki S., Evensen Ø. (2016). Chapter 5 – Prevention and control of viral diseases in aquaculture. In: Aquaculture virology, Kibenge F.S.B., Godoy M.G. (eds). San Diego, Academic Press, pp. 77–93.

Naiel M.A.E., Ismael N.E.M., Shehata S.A. (2019). Ameliorative effect of diets supplemented with rosemary (*Rosmarinus officinalis*) on aflatoxin B1 toxicity in terms of the performance, liver histopathology, immunity and antioxidant activity of Nile tilapia (*Oreochromis niloticus*). Aquaculture, 511: 734264.

Naiel M.A.E., Ismael N.E.M., Negm S.S., Ayyat M.S., Al-Sagheer A.A. (2020). Rosemary leaf powder–supplemented diet enhances performance, antioxidant properties, immune status, and resistance against bacterial diseases in Nile tilapia (*Oreochromis niloticus*). Aquaculture, 526: 735370.

Naiel M.A.E., Alagawany M., Patra A.K., El-Kholy A.I., Amer M.S., Abd El-Hack M.E. (2021). Beneficial impacts and health benefits of macroalgae phenolic molecules on fish production. Aquaculture, 534: 736186.

Oniszczuk T., Oniszczuk A., Gondek E., Guz L., Puk K., Kocira A., Kusz A., Kasprzak K., Wójtowicz A. (2019). Active polyphenolic compounds, nutrient contents and antioxidant capacity of extruded fish feed containing purple coneflower (*Echinacea purpurea* (L.) Moench.). Saudi J. Biol. Sci., 26: 24–30.

Pandey K.B., Rizvi S.I. (2009). Plant polyphenols as dietary antioxidants in human health and disease. Oxid. Med. Cell. Longev., 2: 897484.

Pietta P., Minoggio M., Bramati L. (2003). Plant polyphenols: Structure, occurrence and bioactivity. In: Studies in natural products chemistry, Rahman A.-U. (ed.), 28: 257–312.

Prasad V.G.N.V., Krishna B.V., Swamy P.L., Rao T.S., Rao G.S. (2014). Antibacterial synergy between quercetin and polyphenolic acids against bacterial pathogens of fish. Asian Pac. J. Trop. Dis., 4: S326–S329.

Ramezani F., Shekarabi S.P.H., Mehrgan M.S., Foroudi F., Islami H.R. (2021). Supplementation of Siberian sturgeon (*Acipenser baerii*) diet with barberry (*Berberis vulgaris*) fruit extract: Growth performance, hemato-biochemical parameters, digestive enzyme activity, and growth-related gene expression. Aquaculture, 540: 736750.

Salehi B., Mishra A.P., Nigam M., Sener B., Kilic M., Sharifi-Rad M., Tsouh Fokou P.V., Martins M., Sharifi-Rad J. (2018). Resveratrol: A double-edged sword in health benefits. Biomedicines, 6: 91.

Salehi M., Soltani M., Hosseini-Shekarabi S.P. (2016). Effects of antifungal activity of Daenensis thyme (*Thymus daenensis*) and Mentha (*Mentha longifolia*) essential oils on rainbow trout (*Oncorhynchus mykiss*) eggs hatchability. Iran. J. Aquat. Anim. Health, 2: 97–107.

Samavat Z., Shamsaie Mehrgan M., Jamili S., Soltani M., Hosseini Shekarabi S.P. (2019). Determination of grapefruit (*Citrus paradisi*) peel extract bio-active substances and its application in Caspian white fish (*Rutilus frisii kutum*) diet: Growth, haemato-biochemical parameters and intestinal morphology. Aquac. Res., 50: 2496–2504.

Santos L., Ramos F. (2018). Antimicrobial resistance in aquaculture: Current knowledge and alternatives to tackle the problem. Int. J. Antimicrob. Agents, 52: 135–143.

Shekarabi S.P.H., Javarsiani L., Mehrgan M.S., Dawood M.A.O., Adel M. (2022 a). Growth performance, blood biochemistry profile, and immune response of rainbow trout (*Oncorhynchus mykiss*) fed dietary Persian shallot (*Allium stipitatum*) powder. Aquaculture, 548: 737627.

Shekarabi S.P.H., Mehrgan M.S., Ramezani F., Dawood M.A.O., Van Doan H., Moonmanee T., Abdul Hamid N.K., Kari Z.A. (2022 b). Effect of dietary barberry fruit (*Berberis vulgaris*) extract on immune function, antioxidant capacity, antibacterial activity, and stress-related gene expression of Siberian sturgeon (*Acipenser baerii*). Aquac. Rep., 23: 101041.

Song K., Ling F., Huang A., Dong W., Liu G., Jiang C., Zhang Q., Wang G. (2015). *In vitro* and *in vivo* assessment of the effect of antiprotozoal compounds isolated from *Psoralea corylifolia* against *Ichthyophthirius multifiliis* in fish. Int. J. Parasitol. Drugs Drug Resist., 5: 58–64.

Sudheesh P.S., Al-Ghabshi A., Al-Mazrooei N., Al-Habsi S. (2012). Comparative pathogenomics of bacteria causing infectious diseases in fish. Int. J. Evol. Biol., 1–16.

Taguri T., Tanaka T., Kouno I. (2004). Antimicrobial activity of 10 different plant polyphenols against bacteria causing food-borne disease. Biol. Pharm. Bull., 27: 1965–1969.

Tsimogiannis D., Oreopoulou V. (2019). Chapter 16 – Classification of phenolic compounds in plants. In: Polyphenols in plants, Watson R.R. (ed.). 2nd edition. Academic Press, pp. 263–284.

Vaseeharan B., Thaya R. (2014). Medicinal plant derivatives as immunostimulants: an alternative to chemotherapeutics and antibiotics in aquaculture. Aquac. Int., 22: 1079–1091.

Vincent A.T., Gauthier J., Derome N., Charette S.J. (2019). The rise and fall of antibiotics in Aquaculture. In: Microbial communities in aquaculture ecosystems: Improving productivity and sustainability, Derome N. (ed.). Cham: Springer International Publishing, pp. 1–19.

Wang K., Conlon M., Ren W., Chen B.B., Bączek T. (2018). Natural products as targeted modulators of the immune system. J. Immunol. Res., 7862782.

Watts J.E.M., Schreier H.J., Lanska L., Hale M.S. (2017). The rising tide of antimicrobial resistance in aquaculture: Sources, sinks and solutions. Mar. Drugs, 15: 158.

Yahfoufi N., Alsadi N., Jambi M., Matar C. (2018). The immunomodulatory and anti-inflammatory role of polyphenols. Nutrients, 10: 1618.

Yanong R.P.E. (2003). Fungal diseases of fish. Vet. Clin. North. Am. Exot. Anim. Pract., 6: 377–400.

Zhao G., Chung K.-T., Milow K., Wang W., Stevens Jr S.E. (1997). Antibacterial properties of tannic acid and related compounds against the fish pathogen *Cytophaga columnaris*. J. Aquat. Anim. Health, 9: 309–313.

Received: 29 X 2022
Accepted: 9 I 2023