Fishery Technology 61 (2024) : 293 - 304

Exploring Botanical Innovations in Fish Aquaculture: A Review of Biological Impacts and Industry Prospects

Krishnaveni C.[1], Hridya T. A.[1], Nahid K.[1], Jyothika B.[1], Keerthi G. R.[1], Jhanani G.[1], Krishnakumar V.[1]*, Divya K. R.[2] and Majesh T.[1]

[1] *Department of Life Sciences, Christ University, Hosur Road, Dharmaram College Post, Bengaluru, Karnataka - 560 029, India*

[2] *Department of Zoology, Bharathiyar University, Coimbatore, Tamilnadu, India*

Abstract

Culture fisheries play a crucial role in providing protein-rich sustenance for the expanding global population. However, the intensification of fish farming comes with a downside – heightened stress among fish, which subsequently escalates the risk of disease transmission. The emergence of resilient bacterial populations and the accumulation of residues in body tissues due to the use of drugs and chemicals have underscored the necessity for the development of environmentally friendly and durable solutions. Notably, there has been a recent upsurge in interest regarding the use of botanical products to enhance aquaculture practices. Plant-derived secondary metabolites have demonstrated their efficacy in stimulating appetite, facilitating growth, boosting immune responses, and exhibiting antibacterial as well as anti-parasitic properties within the realm of aquaculture. This article aims to comprehensively examine the body of research on the application of plant-derived products in pisciculture, elucidating their effects on various biological aspects of fish, including growth patterns, immune system functionality, pigmentation, blood composition, and reproductive parameters. Furthermore, the article also delivers inputs into an assessment of the current status of these practices, the methodologies deployed, and the challenges encountered in integrating plant-based solutions into the aquaculture industry.

Keywords: Aquaculture, fish farming, botanical products, fish stress, environmental solutions

Received 19 December 2023; Revised 18 September 2024; Accepted 20 September 2024

Email: krishnakumar.v@christuniversity.in

Introduction

Over the past few decades, the global demand for seafood, particularly fish, has surged due to population growth and dietary preferences (FAO, 2020). In response, aquaculture has become crucial for supplementing wild fisheries and meeting protein needs (Naylor et al., 2021). However, the intensification of fish farming presents challenges, notably increased susceptibility to stress and diseases (FAO, 2018). High-density conditions amplify disease risks, urging the need for innovative solutions. Conventional antimicrobials pose challenges like antibiotic resistance and residue concerns (Cabello, Godfrey, Buschmann & Dölz, 2016; Martin et al., 2019). The occurrence of horizontal gene transfer of resistance genes between aquacultured species and their surrounding environments to humans is a recognized phenomenon. The aquaculture supply chain may serve as a potential conduit for the dissemination of antimicrobial-resistant bacteria. Due to the open and hydrodynamically connected nature of aquatic ecosystems, microbes can travel passively over distances exceeding 50 kilometers, thereby colonizing new ecosystems. This movement can result in the development of antimicrobial resistance, which is clinically relevant due to aquaculture practices (Rahimi et al., 2022). Although much of the scientific research on medicinal plants in aquaculture has concentrated on identifying their biological activity rather than the natural products themselves, certain plant species have shown significant potential for use in this field. These include ginger (*Zingiber officinale*), pomegranate (*Punica granatum*), Bermuda grass (*Cynodon dactylon*), Indian ginseng (*Withania somnifera*) and garlic (*Allium sativum*). Additionally, algae are considered a rich source of unique bioactive compounds with various bioactivities (Reverter, Tapissier-Bontemps, Sasal, & Saulnier, 2017). In this context, botanical products in aquaculture have gained attention for promoting fish health and productivity.

Plant-derived compounds, rich in bioactive compounds, offer benefits such as appetite stimulation, growth promotion, immunostimulation, and antimicrobial activities (Dawood et al., 2020; Hoseinifar, Zou, Paknejad, Ahmadifar, & Doan, 2018). Research on the use of medicinal plants and their derived extracts in aquaculture has increased dramatically in recent years (Reverter, Tapissier-Bontemps, Sarter, Sasal, & Caruso, 2020). While there is still a lack of clarity regarding the precise mechanisms underlying the physiological effects observed in fish, such as the enhancement of specific immune parameters, some research indicates that plant extracts may activate toll-like receptors, which are type I transmembrane proteins involved in the innate immune response. Toll-like receptors, in turn, may activate several pathways involved in cell signaling cascade activation, which in turn may promote a pro-inflammatory response by, for example, upregulating pro-inflammatory cytokine expressions like TNF-á and IL-1â. Ultimately, this could modulate both innate and adaptive immune responses (Vallejos-Vidal, Reyes-López, Teles, & MacKenzie, 2016; Hoseinifar et al., 2020). Though still in its infancy, there is currently a dearth of information regarding the long-term impacts of plant extracts on fish physiology. Additionally, there is a lack of uniformity in the preparation of the extracts and their administration to the fish (Reverter, Bontemps, Lecchini, Banaigs, & Sasal, 2014).

This review explores the biological impacts of botanical innovations on fish physiology, covering growth, immune function, pigmentation, blood composition, and reproductive parameters. It assesses methodologies, challenges, and the integration of plant-based solutions into aquaculture. The goal is to provide insights into how botanical innovations can revolutionize fish farming, contributing to industry growth, sustainability, global food security, and responsible resource utilization.

In the realm of aquaculture, the integration of plant extracts into fish feed formulations serves as a valuable strategy to augment growth, body composition, and feed consumption (Talpur, 2014; Shakya & Labh, 2014). The evaluation of growth metrics encompasses various parameters such as metabolic growth rate (MGR), protein efficiency ratio (PER), specific growth rate (SGR), relative growth rate (RGR), weight gain rate (WGR), survival rate, and carcass composition (Francis, Makkar, & Becker, 2001; Hu, Zhang, Xue, Chu, & Hu, 2021). Plants, in their defense mechanism against predators and microbes, synthesize secondary metabolites including terpenoids, alkaloids, and phenolics (Zaynab et al., 2018; Wianowska & Gil, 2019). Notably, saponins, a class of surface-active secondary metabolites, have been a subject of experimentation for improving the growth and survival of aquatic organisms (Zhu et al., 2019). Specifically, Quillaja saponin (QS) derived from *Quillaja saponaria* has exhibited enhancements in parameters such as MGR, PER, protein productivity, apparent lipid conversion, lipid content, as well as body weight gain, final body weight, and SGR in *Oreochromis niloticus* (Francis et al., 2001; Elkaradawy et al., 2021).

Furthermore, the application of saponins has been linked to heightened nutrient digestibility through the augmentation of enzymatic activities of gut enzymes like amylase, lipase, and trypsin, thereby facilitating favourable feed utilisation in species such as *O. niloticus* and *Cyprinus carpio* (Francis, Makkar, & Becker, 2005; Serrano, 2013). This growth-promoting mechanism is attributed to the increased intestinal membrane permeability, leading to improved nutrient absorption (Serrano, 2013; Chen et al., 2011; Gopalraaj, Velayudhannair, Arockiasamy, & Radhakrishnan, 2023). The rise in lipid content in the carcass might be because saponins cause muscles to make cholesterol de novo (Chavali, Francis, & Campbell, 1987). Another noteworthy growth-promoting agent is the bark of *Cinnamomum camphora*, which has demonstrated its efficacy in enhancing growth-related parameters in *O. niloticus* (Kareem, Abdelhadi, Christianus, Karim, & Romano, 2016). The application of *C. camphora* has led to improvements in feed intake, feeding efficiencies, crude protein, and lipid content, while also exhibiting prophylactic properties that contribute to decreased fish mortality rates and consequently improved survival. It is thought that compounds like 1,8-cineole and α-terpineol help plants absorb nutrients better and fight off microbes more effectively (Abdelhamid & Soliman, 2012; Klûga, Terentjeva, Vukovic, & Kaèániová, 2021).

Likewise, the incorporation of *Mentha piperita*, a perennial herb containing menthol, mentofuran, isomenthone, 1,8-cineole, and menthyl acetate, as a dietary supplement in *Catla catla* has demonstrated growth-promoting effects (Saluja & Bhatnagar, 2023). Administering this herb to *Rutilus frisii kutum* (Adel, Amiri, Zorriehzahra, Nematolahi, & Esteban, 2015) and *Rutilus caspicus* (Paknejad et al., 2020) has also shown improvements in weight and specific growth. The extract from *M. piperita* stimulates the production of growth hormone (GH) and insulin-like growth factor (IGF), consequently enhancing nutrient utilisation in fish (Paknejad et al., 2020). In a similar vein, the dietary inclusion of *Psidium guajava* L. has led to elevated final body weight, percentage weight gain, and SGR in *Labeo rohita* (Giri et al., 2015) and *O. mossambicus* (Gobi et al., 2016; Abdel-Tawwab & Hamed, 2020). The bioactive compounds present in the leaves, including phenols, saponins, and flavonoids, have contributed to improved growth performance through the efficient secretion of digestive enzymes and enhanced nutrient management (Tambe, Singhal, Bhise, & Kulkarni, 2014; Souza et al., 2019; Omitoyin et al., 2019).

Additionally, the influence of plant extracts on fish growth and survival extends to species such as *Solea senegalensis* post-larvae, where curcumin extracted from *Curcuma longa* has been observed to regulate genes associated with muscle development, subsequently impacting growth and survival. The antioxidative properties of curcumin further contribute by reducing oxidative stress and allowing for redirected energy towards growth (Xavier et al., 2020; Xavier et al., 2021). While considering the growth and survival of fish, factors such as species type, size, dosage of dietary supplements, nutritional and physiological status of the fish, as well as culturing conditions, play pivotal roles (Akrami, Gharaei, Mansour, & Galeshi, 2015). Notably, extracts derived from various parts of different plant species have shown the potency to significantly influence the composition and performance of fish within aquaculture settings.

With significant growth of aquaculture, fish encounter an array of challenges spanning physical, chemical, biological, and procedural realms throughout their life cycle (Gabriel & Akinrotimi, 2011). To combat these challenges, fish possess a dual arsenal of innate and acquired immunity (Uribe, Folch, Enriquez, & Moran, 2011). In large-scale fish production, chemicals are often employed to boost fish immunity against specific microbes or parasites, delivered through feed or dip treatments. However, an alternative lies in plant extracts, enriched with antimicrobial and antibacterial properties owing to phytochemical attributes like tannins, alkaloids, monoterpenes, and more. Abutbul, Golan-Goldhirsh, Barazani and Zilberg (2004) demonstrated that the ethyl acetate extract of rosemary (*Rosmarinus officinalis*) leaves (1:24 w/w) curbed mortality rates in *Streptococcus iniae*-infected tilapia by compounds like camphor, terpineol-4-ol, -terpineol and rosmarinic acid with antibacterial potency. Similarly, a robust immunostimulant effect against *Vibrio parahaemolyticus* was found in *Penaeus indicus* juveniles fed *Ricinus communis* extract powder (400 mg/L) via bioencapsulated Artemia, attributed to ricinine, a lectin protein found within castor bean with potent antibacterial properties (Immanuel, Vincybai, Sivaram, Palavesam, & Marian, 2004; Al-Mamun et al., 2016). Harikrishnan, Rani, and Balasundaram (2003) found that an ethyl alcohol extract (10% v/v) of *Azadirachta indica* leaf mitigated *Aeromonas hydrophila* infection in common carp, resulting in a notable increase in serum glucose, cholesterol, total protein, red blood cells, haemoglobin, and packed cell volume, attributed to the extract's particulate and soluble constituents. Also, an aqueous extract (150 mg/l) of the same leaves was effective against *Citrobacter freundii* bacteria in tilapia fingerlings. This was due to phytochemicals such as coumarins, saponin alkaloids, phlobatannins and tannins (Thanigaivel et al., 2015). *Prunus domestica* aqueous methanolic extract (0.1%) exhibited antioxidant, antimicrobial and anti-inflammatory prowess attributed to 13-Docosenamide (Z) and 9-Octadecenamide components, effectively combating *Yersinia ruckeri* infection in rainbow trout (Terzi et al., 2021). In the context of *Vibrio harveyi* bacteria in *Epinephelus tauvina*, active compounds such as cyanodin and hydrocyanic acid in *Cynodon dactylon* and *Phyllanthin, phyllochrysine,* and quercitrin in *Phyllanthus niruri* were observed to elevate the phagocytotic activity (Punitha et al., 2008). Administration of these extracts at 400 mg/kg through the feed proved efficacious.

Indian almond (*Terminalia catappa*) water extract (800 ppm) eradicated *Trichodina* sp. parasites in infected tilapia fishes, attributed to the presence of tannic acid within the leaves (Chitmanat, Tongdonmuan, Khanom, Pachontis, & Nunsong ,2005; Chansue & Assawawongkasem, 2008). Notably, the methanol extract of *Macleaya cordata* (25.5 mg/L) demonstrated potent anthelmintic efficacy against the *Gyrodactylus* *kobayashii* parasite in goldfish when dissolved in water, driven by alkaloids like saguinarine, chelerythrine, and allocryptopine, showcasing nematicidal activity against *Bursaphelenchus xylophilus*, *Caenorhabditis elegans*, and *Meloidogyne incognita* (Zhou et al., 2017; Wang et al., 2012). Furthermore, rosemary ethanol extract (168 mL/kg) exhibited anthelmintic properties against *Zeuxapta seriolae* parasites in yellowtail kingfish, spearheaded by the phytochemical 1,8-cineolentic (Ingelbrecht et al., 2020). This was reinforced by the oral administration of aqueous rosemary leaf extract (80–100 ml/100 g feed) to *C. carpio* afflicted by *Dactylogyrus minutus*, a monogenean parasite (Zoral, Futami, Endo, Maita, & Katagiri, 2017).

Fish serve as valuable indicators for assessing the impact of environmental pollutants due to their high sensitivity to biochemical and hematological changes. Their responsiveness aids in deciphering the physiological alterations occurring in the presence of varying pollutant concentrations (Talas & Gulhan, 2009). The exploration of hematological parameters provides insights into both structural and functional effects on animals exposed to toxins leveraging the susceptibility of blood to environmental and physiological shifts. Profiling the levels of fish plasma emerges as a partial yet informative approach to detecting aquatic stress (Suvetha, Ramesh, & Saravanan, 2010). In a comprehensive work to gauge the influence of the ethanolic extract derived from the bark of *Terminalis arjuna* on freshwater stinging catfish (*Heteropneustes fossilis*), the results revealed noteworthy alterations. Among these changes, a significant increase in the mean corpuscular volume, mean corpuscular hemoglobin, white blood cell count, and plasma glucose concentration was observed, when compared with the control group (Suely et al., 2016). Similar results were reported by Latha, Krishnakumar, and Munuswamy (2020) with freshwater catfish, *Pangasius sutchi*, fed with *Tinospora cordifolia* leaf extract. Elevating glucose levels could be attributed to factors such as hyperglycemia or the involvement of stress-related hormones like corticosteroids or catecholamines (Mekkawy, Mahmoud, & Mohammed, 2013). Concurrently, the increase in white blood cell count might be a response to the presence of toxic conditions, indicating an active role in dealing with the stressor (Harabawy & Ibrahim, 2014).

In common carp (*C. carpio*), the administration of *Moringa oleifera* seed extract (124.0 mg/L) produced significant effects. This included heightened aspartate aminotransferase (AST), alanine aminotransferase (ALT), and alkaline phosphatase (ALP) activity, along with an elevation in white blood cell count, mean corpuscular volume, and mean corpuscular hemoglobin (Kavitha, Ramesh, Kumaran, & Lakshmi, 2012). The increased white blood cell count serves as an indicator of the organism's response to toxic stress, potentially associated with lymphopoiesis (Ates, Orun, Talas, Durmaz, & Yilmaz, 2008). The rise in MCV and MCH values could be attributed to erythrocyte swelling, a phenomenon pointed out in previous studies (Brucka-Jastrzebska & Protasowicki, 2005).

Furthermore, the augmented activity of ALP might be linked to cytotoxicity resulting from the seed extract, while the elevation of AST and ALT could stem from disruptions in the Krebs cycle or organ damage, leading to the release of enzymes into the bloodstream and subsequent elevation of plasma levels. Erythrocytes and haemoglobin play pivotal roles in oxygen delivery and toxin transfer to the gills for excretion. The impact of *Zingiber officinale* (ginger) supplementation was investigated in common carp (*C. carpio*). This natural antioxidant exhibited the ability to prevent the hemolysis of red blood cells (RBCs) by free radicals, consequently extending their lifespan. Moreover, ginger intake elevated leukocyte levels and certain serum components, including total protein, albumin, and globulin (Mohammadi, Rashidian, Hoseinifar, Naserabad, & Doan, 2020). Similar observations were made in studies involving Rainbow Trout (*Oncorhynchus mykiss*), where dietary ginger supplements yielded analogous results (Nya & Austin, 2009). Likewise, the administration of leaf extract from *Origanum marjorana* led to boosted levels of RBCs, MCH, and MCV in *C. carpio* as compared to the control group (Yousefi, Gharfarifarsani, Hoseinifar, Rashidian, & Doan, 2021). Delving into the dietary effects, the introduction of *Mentha piperita* to Caspian White Fish Fry (*Rutilus frissi kutum*) demonstrated dose-dependent enhancements in various hematological parameters. The increments in total RBCs, hematocrit and hemoglobin values correlated with the extract dosage in each group. Intriguingly, the impact on blood cells varied depending on leucocyte type, varied depending on leucocyte type, yielding a nuanced response. These findings suggested enhanced immunological benefits from the supplementation (Adel et al., 2015).

The aquaculture sector has increasingly directed its attention towards the cultivation of aquarium fish. The vibrant colors and appealing physical attributes of ornamental fish stand as pivotal determinants of consumer interest and market demand worldwide. Consequently, the formulation of fish feed by fish farmers has gained paramount importance, with the incorporation of diverse carotenoids, sourced from either natural or synthetic origins, to achieve the desired coloration of fish flesh integument. Chromatophores, which include melanophores, xanthophores, erythrophores, iridophores, leucophores, and cyanophores, are mainly responsible for the colour of ornamental fish species (Grether, Hudon, & Endler, 2001). Among vertebrates, the three primary pigments that contribute to the distinctive colouring of the integument are melanins, pterins, and carotenoids (Clotfelter, Ardia, & McGraw, 2007; Sefc, Brown, & Clotfelter, 2014). It has been elucidated that chromatophores within fish carry carotenoids, hinting at the possibility of colour shifts for purposes such as camouflage (Hatlen, Arnesen, Jobling, Siikavuopio, & Bjerkeng, 1997). The spectrum of carotenoids in fish pigmentation encompasses a range from yellow tunaxanthin, greenish-yellow lutein, and orange beta-carotene to orange alpha/beta-doatoxanthins, yellow-orange zeaxanthin, orange-red canthaxanthin, pink-red astaxanthin, red eichinenone, and yellow taraxanthin. Notably, among these, astaxanthin is the most common carotenoid found in red-coloured fish. Lutein is prevalent in many freshwater fish, while marine species frequently contain lutein and other carotenoids (Gupta, Jha, Pal, & Venkateshwarlu, 2007). Notably, while animals are capable of producing melanins and pterins, the generation of carotenoids is beyond their physiological capabilities. Consequently, dietary consumption of carotenoids, whether from natural or synthetic sources, is necessary to bestow these substances with their characteristic colouration (Kumar et al., 2017). In a study involving goldfish (*Carassius auratus*) and ornamental Koi carp, the utilization of extracts from three different plants, namely the African tulip tree flower, red paprika, and pomegranate peel, showed encouraging results. Notably, the impact of paprika appeared to be more pronounced on Koi carp in comparison to goldfish. Interestingly, goldfish exhibited a more intense red colouration. Over several months of administering feed incorporating paprika, discernible differences in the intensity of red color between the control group and the paprika-fed group became apparent (Saikia & Das, 2023). Further studies have been conducted involving goldfish fed with marigold (*Tagetes erecta*)-infused feed. These investigations concluded that the natural plant extracts mentioned earlier can be effectively utilized as feed for goldfish and Koi carp at 5% of the dietary level without adversely affecting their survival and growth. These vivid colourations in ornamental fish are not just visually appealing but also play a decisive role in determining their ornamental value in the market. Exploring the dietary impacts, a study involving electric yellow cichlid (*Labidochromis caeruleus*) considered the use of nettle (*Urtica* sp.), marigold (*Tagetes erecta*), alfalfa (*Medicago sativa*) extracts, and synthetic xanthophyll (zeaxanthin) carotenoid supplementations. Initially, no substantial effects of the plant extracts or the carotenoid supplement were observed. However, as time progressed, the treatment effects became evident. Given the yellow hue of the chosen fish species, experimental plants rich in carotenoids were selected to achieve the desired effect. The carotenoid-supplemented groups manifested the desired skin hue, with the natural extracts notably enhancing pigmentation. The skin color of the carotenoid-supplemented groups exhibited a purer and brighter appearance compared to the control group. The potential of natural materials as feed additives has also been explored for aquaculture species like sea bream.

Animal colours bear significance for communication, ecological dynamics, and speciation. Carotenoids also play a pivotal role in mating-related sexual attraction. The phenomenon of colour change is particularly evident in salmonids, where the skin colour shifts due to the mobilization of astaxanthin from flesh to skin during maturation (Craik & Harvey, 1987). Investigations involving brown trout (*Salmo trutta*) fry showed the deposition of carotenoids in chromatophores as a primary fate of carotenoids stored within the yolk sac (Das & Biswas, 2016). Similarly, Atlantic salmon fry displayed a significant transfer of carotenoids from the yolk sac to the integument (National Research Council, 1993). Astaxanthin is notably responsible for the red integumentary colouration observed in most freshwater and marine teleost fish, while lutein and tunaxanthin contribute to the yellow hue in other teleost fish. Distinct examples of these colouration mechanisms include the yellowtail (*Seriola quinqueradiata*) and red sea bream (*Pagrus major*), both exhibiting tunaxanthin deposition in their skin, primarily derived from dietary astaxanthin.

In goldfish and stunning red carp, the yellow pigment zeaxanthin is readily converted into astaxanthin, lending the skin its signature pink-red hue (Ansari, Guldhe, Gupta, Rawat, & Bux, 2021).

Tilapia, *O. niloticus*, holds a significant position in the realm of traded food fish and is a vital species in aquaculture endeavors. Nonetheless, the challenges of premature maturity and uncontrolled reproduction have prevented Tilapia from fully realizing their aquaculture potential, often leading to issues of overpopulation. In response to this, various strategies have been devised, such as introducing predators, same-sex culture, and hormone-induced sex reversal (Sonmez, Ozdemir, Bilen, & Kadak, 2019). However, these strategies come with their inherent limitations, requiring skilled labour, costly facilities, and technologies. In light of this, a novel approach emerged involving the incorporation of *Aloe vera* latex into fish feed with the aim of monitoring gonad development and reproduction rates. The sexual maturity of Tilapia typically takes about 3-5 months, and during each spawning, it produces a remarkable 1500–2000 eggs. Throughout the specified culture duration, the fish were provided with appropriate feed, and their gonad development was meticulously observed. Notably, as the concentration of *Aloe vera* latex increased in the diet, sperm motility exhibited a significant decrease. Similarly, among female tilapia, an increase in the concentration of *A. vera* latex in their diet led to a decline in fecundity and egg size. At higher concentrations, such as 1.5 ml and 2.0 ml, symptoms including changes in ovarian color, ruptured follicles, interstitial inflammation, and aberrant cell growth, ultimately progressing to ovarian necrosis, were evident (Sonmez et al., 2019).

Another study on the effects of Ginseng root extracts on the reproductive and gonadal capacities of Rainbow Trout (*Oncorhynchus mykiss*) (Mehrim, Refaey, Hassan, Zaki, & Zenhom, 2022). Ginseng was incorporated into the feed, and parameters such as sperm density, motility, and motility duration were employed to assess sperm quality. Given the strong correlation between sperm motility and fish reproductive performance, heightened motility often translates to increased reproduction. The results demonstrated that elevated concentrations of ginseng meal led to improved sperm motility within the experimental groups as compared to the control group. Furthermore, the experimental groups exhibited higher fertilization ratios than the control group, suggesting that the data could be harnessed to select high-quality males for optimal fertilization and reproduction (Mehrim et al., 2022).

In a different study, the potential use of varying doses of ginseng extract to enhance male African catfish (*Clarias gariepinus*) reproduction was examined (Gholampour et al., 2020). The findings revealed that fish consuming a diet rich in ginseng experienced improvements in various parameters, including histological testis structure, gonadal-somatic index, serum follicle-stimulating hormone, sperm quality, and spermatozoa ultrastructure, when compared to other treatments. Similarly, the efficacy of *Desmodium adsendences* leaf extracts as dietary supplements for male and female *Clarias gariepinus* (African catfish) was explored, demonstrating enhancements in gamete quality, and increased pro-fertility attributes (Kapinga et al., 2019). A four-month study encompassing four different fish feed types (fish meal, soybean meal, pea meal, and commercial Tilapia feed) with a 36% protein content and three different temperatures (24°C, 28°C, and 32°C) yielded interesting insights (Oke, Dada, Saliu, & Kuyoro, 2019). Fish meal diets demonstrated the most significant weight gain and female gonadosomatic index (GSI) increase. The GSI, which represents the gonad mass to total body weight ratio, pointed towards optimal growth and development at 28°C. Furthermore, it was observed that as temperatures approached 32°C, female GSI decreased, suggesting that 28°C was the ideal temperature for catfish in terms of GSI. In a study involving the dietary effect of *Vitex agnus-castus* hydroalcoholic extract on the reproduction and gonadal histology of Zebrafish (*Danio rerio*), this phytoestrogen demonstrated potential in enhancing growth metrics among zebrafish, a species increasingly employed in aquaculture research due to its rapid growth and visibility, making it a model organism for vertebrate development (Soutoudeh & Yeganeh, 2016). This study hinted at the feasibility of utilising *Vitex agnus-castus* as a natural fish feed supplement within commercial aquaculture to enhance fertility. Exploring the effects of nettle extracts (*Urtica dioica*) on the reproductive parameters of convict cichlid (*Amatitlania nigrofasciata)* revealed that low concentrations of nettle extracts in their diets contributed to increased egg and embryo quantities, as well as elevated hatching rates (Jafari, Abdollahpour, Karimzadeh, & Falahatkar, 2022). Furthermore, investigations focusing on dietary supplementation involving *Aspilia mossambicensis* and *Azadirachta indica* found alterations in gonadal characteristics and histology in juvenile Nile tilapia (*O. niloticus*) (Gabriel et al., 2015). This study indicated that *Aspilia mossambicensis* and *Azadrachita indica* leaf powders could indeed influence gonadal histology and diminish gonadal characteristic indices in *O. niloticus*. The potential of *Tribulus terrestris* plant extract was also explored, unveiling heightened testosterone levels in male *Tilapia* and subsequently enhancing their reproductive capacity (Gabriel, 2019; Hassona, Zayed, Eltras, & Mohamed, 2020). Various plant extracts exert diverse effects on the reproductive and gonadal nature of aquaculture-reared fish, influenced by factors such as extract concentration, type of fish feed, temperature, and more. The potential of herbal extracts to influence reproduction, either directly or indirectly through hormone regulation, emerges as a promising avenue for further exploration.

Conclusion

In conclusion, the future prospects of utilizing plant metabolites in fish aquaculture are bright. As the global demand for seafood continues to rise, the aquaculture industry stands as a vital source of aquatic food products. However, the intensification of fish culture has brought about new challenges, particularly in the form of increased stress and disease susceptibility among farmed fish. Traditional approaches involving antimicrobial agents, while effective, come with concerns about antibiotic resistance and the accumulation of residues in fish tissues, prompting the need for ecologically friendly and sustainable alternatives. The application of botanical products enriched with bioactive compounds like alkaloids, terpenoids, saponins, and flavonoids has emerged as a promising solution for improving growth and survival, immunological parameters, body pigmentation, and reproductive performance in fish. However, it is important to acknowledge that the effects of plant metabolites can vary based on factors such as species, dosage, nutritional status, and environmental conditions. Further research is needed to fine-tune the integration of plant-based solutions into the aquaculture industry and optimize their benefits. These eco-friendly alternatives not only promote sustainable aquaculture but also contribute to the broader goals of global food security and responsible resource utilization. As research in this field continues to evolve, a brighter and more sustainable future for the aquaculture industry, with plant metabolites playing a pivotal role in its growth and development is anticipated.

The exploration of impact of plant metabolites on various aspects of fish aquaculture has unveiled a promising future with several potential prospects. As we delve deeper into this field, future prospects for research and practical applications, such as refinement of dosage and formulations, development of targeted solutions for specific challenges, exploration of new plant sources rich in beneficial compounds, combining plant metabolites with other innovations, such as probiotics, biotechnology, or advanced aquaculture systems are apparent. Continuous monitoring and assessment of the long-term effects of plant-based solutions on fish health, product quality, and the environment will also be crucial.

Acknowledgements

We extend our heartfelt gratitude to Dr. Fr. Jobi Xavier, Head of the Department of Life Sciences, Christ University for his constant encouragement. We also thank the anonymous reviewers for their critical comments, which greatly helped improve this manuscript.

References

Abdelhamid, A. M., & Soliman, A. A. A. (2012). Possibility of using dried leaves of guava and camphor trees in tilapia diets. *Journal of the Arabian Aquaculture Society*, *7*(1), 91-108.

Abdel-Tawwab, M., & Hamed, H. S. (2020). Antagonistic effects of dietary guava (*Psidium guajava*) leaves extract on growth, hemato-biochemical, and immunity response of cypermethrin-intoxicated Nile tilapia, *Oreochromis niloticus*, fingerlings. *Aquaculture*, *529*, 735668. https://doi.org/10.1016/j.aquaculture.2020.735668.

Abutbul, S., Golan-Goldhirsh, A., Barazani, O., & Zilberg, D. (2004). Use of *Rosmarinus officinalis* as a treatment against *Streptococcus iniae* in tilapia (*Oreochromis sp*.). *Aquaculture*, *238*(1–4), 97–105. https://doi.org/10.1016/j.aquaculture.2004.05.016.

Adel, M., Amiri, A. A., Zorriehzahra, J., Nematolahi, A., & Esteban, M. A. (2015). Effects of dietary peppermint (*Mentha piperita*) on growth performance, chemical body composition and hematological and immune parameters of fry Caspian white fish (*Rutilus frisii kutum*). *Fish & Shellfish Immunology*, *45*(2), 841–847. https://doi.org/10.1016/j.fsi.2015.06.010.

Akrami, R., Gharaei, A., Mansour, M. R., & Galeshi, A. (2015). Effects of dietary onion (*Allium cepa*) powder on growth, innate immune response and hemato–

biochemical parameters of beluga (*Huso huso* Linnaeus, 1754) juvenile. *Fish & Shellfish Immunology*, *45*(2), 828–834. https://doi.org/10.1016/j.fsi.2015.06.005.

Al-Mamun, M. A., Akter, Z., Uddin, M. J., Ferdaus, K. M. K. B., Hoque, K. M. F., Ferdousi, Z., & Reza, M. A. (2016). Characterization and evaluation of antibacterial and antiproliferative activities of crude protein extracts isolated from the seed of Ricinus communis in Bangladesh. *BMC Complementary and Alternative Medicine*, *16*(1), 211. https://doi.org/10.1186/s12906-016-1185-y.

Ansari, F. A., Guldhe, A., Gupta, S. K., Rawat, I., & Bux, F. (2021). Improving the feasibility of aquaculture feed by using microalgae. *Environmental Science and Pollution Research*, *28*(32), 43234–43257. https://doi.org/10.1007/s11356-021-14989-x.

Ates, B., Orun, I., Talas, Z. S., Durmaz, G., & Yilmaz, I. (2008). Effects of sodium selenite on some biochemical and hematological parameters of rainbow trout (*Oncorhynchus mykiss* Walbaum, 1792) exposed to Pb^{2+} and Cu^{2+}. *Fish Physiology and Biochemistry*, *34*(1), 53–59. https://doi.org/10.1007/s10695-007-9146-5.

Brucka-Jastrzêbska, E., & Protasowicki, M. (2005). Effects of cadmium and nickel exposure on haematological parameters of common carp, *Cyprinus carpio* L. *Acta Ichthyologica et Piscatoria*, *35*(1), 29-38.

Cabello, F. C., Godfrey, H. P., Buschmann, A. H., & Dölz, H. J. (2016). Aquaculture as yet another environmental gateway to the development and globalization of antimicrobial resistance. *The Lancet Infectious Diseases*, *16*(7), e127-e133. https://doi.org/10.1016/S1473-3099(16)00100-6.

Chansue, N., & Assawawongkasem, N. (2008). The in vitro antibacterial activity and ornamental fish toxicity of the water extract of Indian almond leaves (*Terminalia catappa* Linn.). *KKU Veterinary Journal*, *18*(1), 36-45.

Chavali, S. R., Francis, T., & Campbell, J. B. (1987). An in vitro study of immunomodulatory effects of some saponins. *International Journal of Immunopharmacology*, *9*(6), 675–683. https://doi.org/10.1016/0192-0561(87)90038-5.

Chen, W., Ai, Q., Mai, K., Xu, W., Liufu, Z., Zhang, W., & Cai, Y. (2011). Effects of dietary soybean saponins on feed intake, growth performance, digestibility and intestinal structure in juvenile Japanese flounder (*Paralichthys olivaceus*). *Aquaculture*, *318*(1–2), 95–100. https://doi.org/10.1016/j.aquaculture.2011.04.050.

Chitmanat, C., Tongdonmuan, K., Khanom, P., Pachontis, P., & Nunsong, W. (2005). Antiparasitic, antibacterial, and antifungal activities derived from a Terminalia catappa solution against some tilapia (*Oreochromis niloticus*) pathogens. *Acta Horticulturae, 678,* 179-182. https://doi.org/10.17660/ActaHortic.2005.678.25.

Clotfelter, E. D., Ardia, D. R., & McGraw, K. J. (2007). Red fish, blue fish: trade-offs between pigmentation and immunity in *Betta splendens*. *Behavioral Ecology*, *18*(6), 1139–1145. https://doi.org/10.1093/beheco/arm090.

Craik, J. C. A., & Harvey, S. M. (1987). A biochemical method for distinguishing between wild and farmed salmonid fishes by their carotenoid pigmentation. *Journal of the Forensic Science Society*, *27*(1), 47–55. https://doi.org/10.1016/s0015-7368(87)72706-6.

Das, A. P., & Biswas, S. P. (2016). Carotenoids and pigmentation in ornamental fish. *Journal of Aquaculture & Marine Biology*, *4*(4), 00093. https://doi.org/10.15406/jamb.2016.04.00093.

Dawood, M. A. O., Metwally, A. E. S., Elkomy, A. H., Gewaily, M. S., Abdo, S. E., Abdel-Razek, M. A. S., Soliman, A. A., Amer, A. A., Abdel-Razik, N. I., Abdel-Latif, H. M. R., & Paray, B. A. (2020). The impact of menthol essential oil against inflammation, immunosuppression, and histopathological alterations induced by chlorpyrifos in Nile tilapia. *Fish & Shellfish Immunology*, *102*, 316–325. https://doi.org/10.1016/j.fsi.2020.04.059.

Elkaradawy, A., Abdel-Rahim, M. M., Albalawi, A. E., Althobaiti, N. A., Abozeid, A. M., & Mohamed, R. A. (2021). Synergistic effects of the soapbark tree, *Quillaja saponaria* and Vitamin E on water quality, growth performance, blood health, gills and intestine histomorphology of Nile tilapia, *Oreochromis niloticus* fingerlings. *Aquaculture Reports*, *20*, 100733. https://doi.org/10.1016/j.aqrep.2021.100733.

FAO. (2018). *The State of World Fisheries and Aquaculture 2018 - Meeting the sustainable development goals.* FAO, Rome.

FAO. (2020). *Progress towards development of the progressive management pathway for improving aquaculture biosecurity (PMP/AB): Highlights of 2019 activities* (1st ed.). FAO, Rome.

Francis, G., Makkar, H. P. S., & Becker, K. (2005). *Quillaja saponins*—a natural growth promoter for fish. *Animal Feed Science and Technology*, *121*(1–2), 147–157. https://doi.org/10.1016/j.anifeedsci.2005.02.015.

Francis, G., Makkar, H. P. S., & Becker, K. (2001). Effects of *Quillaja saponins* on growth, metabolism, egg production and muscle cholesterol in individually reared Nile tilapia (*Oreochromis niloticus*). *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology*, *129*(2), 105–114. https://doi.org/10.1016/s1532-0456(01)00189-2.

Gabriel, N. N. (2019). Review on the progress in the role of herbal extracts in tilapia culture. *Cogent Food & Agriculture*, *5*(1), 1619651. https://doi.org/10.1080/23311932.2019.1619651.

Gabriel, N. N., Qiang, J., He, J., Ma, X. Y., Kpundeh, M. D., & Xu, P. (2015). Dietary *Aloe vera* supplementation on growth performance, some haemato-biochemical parameters and disease resistance against *Streptococcus iniae* in tilapia (GIFT). *Fish & Shellfish Immunology*, *44*(2), 504–514. https://doi.org/10.1016/j.fsi.2015.03.002.

Gabriel, U. U., & Akinrotimi, O. A. (2011). Management of stress in fish for sustainable aquaculture development. *Researcher*, *3*(4), 28-38.

Gholampour, T. E., Raieni, R. F., Pouladi, M., Larijani, M., Pagano, M., & Faggio, C. (2020). The dietary effect of vitex *agnus-castus* hydroalcoholic extract on growth performance, blood biochemical parameters, carcass quality, sex ratio and gonad histology in Zebrafish (*Danio rerio*). *Applied Sciences*, *10*(4), 1402. https://doi.org/10.3390/app10041402.

Giri, S. S., Sen, S. S., Chi, C., Kim, H. J., Yun, S., Park, S. C., & Sukumaran, V. (2015). Effect of guava leaves on the growth performance and cytokine gene expression of *Labeo rohita* and its susceptibility to *Aeromonas hydrophila* infection. *Fish & Shellfish Immunology*, *46*(2), 217–224. https://doi.org/10.1016/j.fsi.2015.05.051.

Gobi, N., Ramya, C., Vaseeharan, B., Malaikozhundan, B., Vijayakumar, S., Murugan, K., & Benelli, G. (2016). *Oreochromis mossambicus* diet supplementation with *Psidium guajava* leaf extracts enhance growth, immune, antioxidant response and resistance to *Aeromonas hydrophila*. *Fish & Shellfish Immunology*, *58*, 572–583. https://doi.org/10.1016/j.fsi.2016.09.062.

Gopalraaj, J., Velayudhannair, K., Arockiasamy, J. P., & Radhakrishnan, D. K. (2023). The effect of dietary supplementation of proteases on growth, digestive enzymes, oxidative stress, and intestinal morphology in fishes – A review. *Aquaculture International*, *32*(1), 745–765. https://doi.org/10.1007/s10499-023-01191-8.

Grether, G. F., Hudon, J., & Endler, J. A. (2001). Carotenoid scarcity, synthetic pteridine pigments and the evolution of sexual coloration in guppies (*Poecilia reticulata*). *Proceedings of the Royal Society of London. Series B: Biological Sciences*, *268*(1473), 1245–1253. https://doi.org/10.1098/rspb.2001.1624.

Gupta, S. K., Jha, A. K., Pal, A. K., & Venkateshwarlu, G. (2007). Use of natural carotenoids for pigmentation in fishes. *Natural Product Radiance*, *6*(1), 46-49.

Harabawy, A. S. A, & Ibrahim, A. T. A. (2014). Sublethal toxicity of carbofuran pesticide on the African catfish *Clarias gariepinus* (Burchell, 1822): Hematological, biochemical and cytogenetic response. *Ecotoxicology and Environmental Safety*, *103*, 61–67. https://doi.org/10.1016/j.ecoenv.2013.09.022.

Harikrishnan, R., Rani, M. N., & Balasundaram, C. (2003). Hematological and biochemical parameters in common carp, *Cyprinus carpio*, following herbal treatment for *Aeromonas hydrophila* infection. *Aquaculture*, *221*(1–4), 41–50. https://doi.org/10.1016/s0044-8486(03)00023-1.

Hassona, N. N., Zayed, M. M., Eltras, W. F., & Mohamed, R. A. (2020). Dietary supplementation of *Tribulus terrestris* extract improves growth and reproductive performances of the male Nile tilapia (*Oreochromis niloticus*). *Aquaculture Research*, *51*(10), 4245–4254. https://doi.org/10.1111/are.14767.

Hatlen, B., Arnesen, A. M., Jobling, M., Siikavuopio, S., & Bjerkeng, B. (1997). Carotenoid pigmentation in relation to feed intake, growth and social interactions in Arctic charr, *Salvelinus alpinus* (L.), from two anadromous strains. *Aquaculture Nutrition*, *3*(3), 189–199. https://doi.org/10.1046/j.1365-2095.1997.00087.x.

Hoseinifar, S. H., Shakouri, M., Doan, H. V., Shafiei, S., Yousefi, M., Raeisi, M., Yousefi, S., Harikrishnan, R., & Reverter, M. (2020). Dietary supplementation of lemon verbena (*Aloysia citrodora*) improved immunity, immune-related genes expression and antioxidant enzymes in rainbow trout (*Oncorrhyncus mykiss*). *Fish & Shellfish Immunology*, *99*, 379–385. https://doi.org/10.1016/j.fsi.2020.02.006.

Hoseinifar, S. H., Zou, H. K., Paknejad, H., Ahmadifar, E., & Doan, H. V. (2018). Non-specific immune responses and intestinal immunity of common carp (*Cyprinus carpio*) fed Jujube (*Ziziphus jujube*) fruit extract. *Aquaculture Research*, *49*(9), 2995–3003. https://doi.org/10.1111/are.13759.

Hu, Y., Zhang, J., Xue, J., Chu, W., & Hu, Y. (2021). Effects of dietary soy isoflavone and soy saponin on growth performance, intestinal structure, intestinal immunity and gut microbiota community on rice field eel (*Monopterus albus*). *Aquaculture*, *537*, 736506. https://doi.org/10.1016/j.aquaculture.2021.736506.

Immanuel, G., Vincybai, V. C., Sivaram, V., Palavesam, A., & Marian, M. P. (2004). Effect of butanolic extracts from terrestrial herbs and seaweeds on the survival, growth and pathogen (*Vibrio parahaemolyticus*) load on shrimp *Penaeus indicus* juveniles. *Aquaculture*, *236*(1–4), 53–65. https://doi.org/10.1016/j.aquaculture.2003.11.033.

Ingelbrecht, J., Miller, T. L., Lymbery, A. J., Maita, M., Torikai, S., & Partridge, G. (2020). Anthelmintic herbal extracts as potential prophylactics or treatments for monogenean infections in cultured yellowtail kingfish (*Seriola lalandi*). *Aquaculture*, *520*, 734776. https://doi.org/10.1016/j.aquaculture.2019.734776.

Jafari, N., Abdollahpour, H., Karimzadeh, M., & Falahatkar, B. (2022). A potential role of nettle (*Urtica dioica*) extract on growth, biochemical changes and reproductive performance of convict cichlid (*Amatitlania nigrofasciata*). *Fish Physiology and Biochemistry*, *48*(1), 133–144. https://doi.org/10.1007/s10695-021-01039-z.

Kapinga, I. B., Limbu, S. M., Madalla, N. A., Kimaro, W. H., Mabiki, F. P., Lamtane, H. A., & Tamatamah, R. A. (2019). Dietary *Aspilia mossambicensis* and *Azadirachta* *indica* supplementation alters reproductive performance and induces gonadal histopathological effects in Nile tilapia (*Oreochromis niloticus*). *Aquaculture Research*, *50*(2), 1-8. https://doi.org/10.1111/are.13931.

Kareem, Z. H., Abdelhadi, Y. M., Christianus, A., Karim, M., & Romano, N. (2016). Effects of some dietary crude plant extracts on the growth and gonadal maturity of Nile tilapia (*Oreochromis niloticus*) and their resistance to *Streptococcus agalactiae* infection. *Fish Physiology and Biochemistry*, *42*(2), 757–769. https://doi.org/10.1007/s10695-015-0173-3.

Kavitha, C., Ramesh, M., Kumaran, S. S., & Lakshmi, S. A. (2012). Toxicity of *Moringa oleifera* seed extract on some hematological and biochemical profiles in a freshwater fish, *Cyprinus carpio*. *Experimental and Toxicologic Pathology*, *64*(7–8), 681–687. https://doi.org/10.1016/j.etp.2011.01.001.

Klûga, A., Terentjeva, M., Vukovic, N. L., & Kaèániová, M. (2021). Antimicrobial activity and chemical composition of essential oils against pathogenic microorganisms of freshwater fish. *Plants*, *10*(7), 1265. https://doi.org/10.3390/plants10071265.

Kumar, P. A., Sudhakaran, S., Mohan, T. C., Pamanna, D., Kumar, P. R., & Shanthanna, P. (2017). Evaluation of colour enhance potential of three natural plant pigment sources (African tulip tree flower, red paprika, pomegranate peel) in goldfish (*Carassius auratus*). *International Journal of Fisheries and Aquatic Studies*, *5*(6), 47-51.

Latha, C., Krishnakumar, V., & Munuswamy, N. (2020). Growth, survival and haemato-biochemical profiles of the freshwater catfish, *Pangasius sutchi* (Fowler, 1937) fingerlings fed on *Tinospora cordifolia* leaf extract supplemented diet. *Egyptian Journal of Aquatic Biology and Fisheries*, *24*(1), 249–262. https://doi.org/10.21608/ejabf.2020.70288.

Martin-Laurent, F., Topp, E., Billet, L., Batisson, I., Malandain, C., Besse-Hoggan, P., Morin, S., Artigas, J., Bonnineau, C., Kergoat, L., Devers-Lamrani, M., & Pesce, S. (2019). Environmental risk assessment of antibiotics in agroecosystems: ecotoxicological effects on aquatic microbial communities and dissemination of antimicrobial resistances and antibiotic biodegradation potential along the soil-water continuum. *Environmental Science and Pollution Research*, *26*, 18930–18937. https://doi.org/10.1007/s11356-019-05122-0.

Mehrim, A. I., Refaey, M. M., Hassan, M. A. E., Zaki, M. A., & Zenhom, O. A. (2022). Ginseng as a reproductive enhancer agent for African catfish, *Clarias gariepinus* (Burchell, 1822). *Fish Physiology and Biochemistry*, *48*, 15–32. https://doi.org/10.1007/s10695-021-00969-y.

Mekkawy, I. A., Mahmoud, U. M., & Mohammed, R. H. (2013). Protective effects of tomato paste and vitamin E on atrazine-induced hematological and biochemical characteristics of *Clarias gariepinus* (Burchell, 1822). *Global Advanced Research Journal of Environmental Science and Toxicology*, *2*(1), 11-21.

Mohammadi, G., Rashidian, G., Hoseinifar, S. H., Naserabad, S. S., & Doan, H. V. (2020). Ginger (*Zingiber officinale*) extract affects growth performance, body composition, haematology, serum and mucosal immune parameters in common carp (*Cyprinus carpio*). *Fish & Shellfish Immunology*, *99*, 267–273. https://doi.org/10.1016/j.fsi.2020.01.032.

National Research Council. (1993). *Nutrient requirements of fish*. National Academies Press, Washington DC.

Naylor, R. L., Hardy, R. W., Buschmann, A. H., Bush, S. R., Cao, L., Klinger, D. H., Little, D. C., Lubchenco, J., Shumway, S. E., & Troell, M. (2021). A 20-year retrospective review of global aquaculture. *Nature*, *591*, 551–563. https://doi.org/10.1038/s41586-021-03308-6.

Nya, E. J., & Austin, B. (2009). Use of dietary ginger, *Zingiber officinale* Roscoe, as an immunostimulant to control *Aeromonas hydrophila* infections in rainbow trout, *Oncorhynchus mykiss* (Walbaum). *Journal of Fish Diseases*, *32*(11), 971–977. https://doi.org/10.1111/j.1365-2761.2009.01101.x.

Oke, I. O., Dada, A. A., Saliu, O. R., & Kuyoro, E. B. (2019). Dietary effects of desmodium (*Desmodium adscendens*) leaves on the reproductive indices in African catfish (*Clarias gariepinus*) broodstock. *Aquaculture Studies*, *19*(2), 133-137. https://doi.org/10.4194/2618-6381-v19_2_06.

Omitoyin, B. O., Ajani, E. K., Orisasona, O., Bassey, H. E., Kareem, K. O., & Osho, F. E. (2019). Effect of guava *Psidium guajava* (L.) aqueous extract diet on growth performance, intestinal morphology, immune response and survival of *Oreochromis niloticus* challenged with *Aeromonas hydrophila*. *Aquaculture Research*, *50*(7), 1851–1861. https://doi.org/10.1111/are.14068.

Paknejad, H., Shekarabi, S. P. H., Mehrgan, M. S., Hajimoradloo, A., Khorshidi, Z., & Rastegari, S. (2020). Dietary peppermint (*Mentha piperita*) powder affects growth performance, hematological indices, skin mucosal immune parameters, and expression of growth and stress-related genes in Caspian roach (*Rutilus caspicus*). *Fish Physiology and Biochemistry*, *46*(5), 1883–1895. https://doi.org/10.1007/s10695-020-00839-z.

Punitha, S. M. J., Babu, M. M., Sivaram, V., Shankar, V. S., Dhas, S. A., Mahesh, T. C., Immanuel, G., & Citarasu, T. (2008). Immunostimulating influence of herbal biomedicines on nonspecific immunity in Grouper *Epinephelus tauvina* juvenile against *Vibrio harveyi* infection. *Aquaculture International*, *16*(6), 511–523. https://doi.org/10.1007/s10499-007-9162-6.

Rahimi, N. N. M. N., Natrah, I., Loh, J. Y., Ranzil, F. K. E., Gina, M., Lim, S. H. E., Lai, K. S., & Chong, C. M. (2022). Phytocompounds as an Alternative Antimicrobial Approach in Aquaculture. *Antibiotics*, *11*(4), 469. https://doi.org/10.3390/antibiotics11040469.

Reverter, M., Bontemps, N., Lecchini, D., Banaigs, B., & Sasal, P. (2014). Use of plant extracts in fish aquaculture as an alternative to chemotherapy: Current status and future perspectives. *Aquaculture*, *433*, 50–61. https://doi.org/10.1016/j.aquaculture.2014.05.048.

Reverter, M., Tapissier Bontemps, N., Sarter, S., Sasal, P., & Caruso, D. (2020). Moving towards more sustainable aquaculture practices: a meta analysis on the potential of plant enriched diets to improve fish growth, immunity and disease resistance. *Reviews in Aquaculture*, *13*(1), 537–555. https://doi.org/10.1111/raq.12485.

Reverter, M., Tappissier-Bontemps, N., Sasal, P., & Saulnier, D. (2017). Use of medicinal plants in aquaculture. *Diagnosis and Control of Diseases of Fish and Shellfish*, *6*, 223–261. https://doi.org/10.1002/9781119152125.ch9.

Saikia, S., & Das, J. N. (2023). Carotenoids as a dietary supplement for enhancing pigmentation and colouration in ornamental fishes: A review. *Uttar Pradesh Journal of Zoology*, *44*(13), 1-16. https://doi.org/10.56557/upjoz/2023/v44i133541.

Saluja, S., & Bhatnagar, A. (2023). Dietary administration of probiotic *Bacillus coagulans* and *Mentha piperita* can protect histological architecture and DNA damage in *Catla catla* (Hamilton, 1822). *Aquaculture and Fisheries*. https://doi.org/10.1016/j.aaf.2023.02.002.

Sefc, K. M., Brown, A. C., & Clotfelter, E. D. (2014). Carotenoid-based coloration in cichlid fishes. *Comparative Biochemistry and Physiology Part A, Molecular & Integrative Physiology*, *173*, 42–51. https://doi.org/10.1016/j.cbpa.2014.03.006.

Serrano Jr, A. E. (2013). Effects of *Quillaja saponins* on growth, feed efficiency, digestive enzyme activities and metabolism of common carp (*Cyprinus carpio* L). *Aquaculture Nutrition*, *19*(4), 468-474. https://doi.org/10.1111/j.1365-2095.2012.00980.x.

Shakya, S. R., & Labh, S. N. (2014). Medicinal uses of garlic (*Allium sativum*) improves fish health and acts as an immunostimulant in aquaculture. *European Journal of Biotechnology and Bioscience*, 2(4), 44-47.

Sonmez, A. Y., Ozdemir, R. C., Bilen, S., & Kadak, A. E. (2019). Effect of ginseng root (*Araliaceae sp.*) extracts on sperm quality parameters and reproductive performance in rainbow trout (*Oncorhynchus mykiss*). *Israeli Journal of Aquaculture-Bamidgeh*, *71*. http://dx.doi.org/10.46989/001c.20992.

Soutoudeh, A., & Yeganeh, S. (2016). Effects of supplementary fennel (*Foeniculum vulgare*) essential oil in diet on growth and reproductive performance of the ornamental fish, Convict cichlid (*Cichlasoma nigrofasciatum*). *Aquaculture Research*, *48*(8), 4284–4291. https://doi.org/10.1111/are.13249.

Sobral-Souza, C. E., Silva, A. R. P., Leite, N. F., Rocha, J. E., Sousa, A. K., Costa, J. G. M., Menezes, I. R. A., Cunha, F. A. B., Rolim, L. A., & Coutinho, H. D. M. (2019). *Psidium guajava* bioactive product chemical analysis and heavy metal toxicity reduction. *Chemosphere*, *216*, 785–793. https://doi.org/10.1016/j.chemosphere.2018.10.174.

Suely, A., Zabed, H., Ahmed, A. B. A., Mohamad, J., Nasiruddin, M., Sahu, J. N., & Ganesan, P. (2016). Toxicological and hematological effect of *Terminalia arjuna* bark extract on a freshwater catfish, *Heteropneustes fossilis*. *Fish Physiology and Biochemistry*, *42*(2), 431–444. https://doi.org/10.1007/s10695-015-0149-3.

Suvetha, L., Ramesh, M., & Saravanan, M. (2010). Influence of cypermethrin toxicity on ionic regulation and gill Na+/K+-ATPase activity of a freshwater teleost fish *Cyprinus carpio*. *Environmental Toxicology and Pharmacology*, *29*(1), 44–49. https://doi.org/10.1016/j.etap.2009.09.005.

Talas, Z. S., & Gulhan, M. F. (2009). Effects of various propolis concentrations on biochemical and hematological parameters of rainbow trout (*Oncorhynchus mykiss*). *Ecotoxicology and Environmental Safety*, *72*(7), 1994–1998. https://doi.org/10.1016/j.ecoenv.2009.04.011.

Talpur, A. D. (2014). *Mentha piperita* (Peppermint) as feed additive enhanced growth performance, survival, immune response and disease resistance of Asian seabass, *Lates calcarifer* (Bloch) against *Vibrio harveyi* infection. *Aquaculture*, *420–421*, 71–78. https://doi.org/10.1016/j.aquaculture.2013.10.039.

Tambe, R., Singhal, R. G., Bhise, K., & Kulkarni, M. (2014). Phytochemical screening and HPTLC fingerprinting of leaf extracts of *Psidium guajava* Linn. *Journal of Pharmacognosy and Phytochemistry*, 3(1), 52-56.

Terzi, E., Kucukkosker, B., Bilen, S., Kenanoglu, O. N., Corum, O., Özbek, M., & Parug, S. S. (2021). A novel herbal immunostimulant for rainbow trout (*Oncorhynchus mykiss*) against *Yersinia ruckeri*. *Fish & Shellfish Immunology*, *110*, 55–66. https://doi.org/10.1016/j.fsi.2020.12.019.

Thanigaivel, S., Vijayakumar, S., Gopinath, S., Mukherjee, A., Chandrasekaran, N., & Thomas, J. (2015). In vivo and in vitro antimicrobial activity of *Azadirachta indica* (Lin) against *Citrobacter freundii* isolated from naturally infected Tilapia (*Oreochromis mossambicus*). *Aquaculture*, *437*, 252–255. https://doi.org/10.1016/j.aquaculture.2014.12.008.

Uribe, C., Folch, H., Enriquez, R., & Moran, G. (2011). Innate and adaptive immunity in teleost fish: a review. *Veterinární Medicína, 56*(10), 486–503. https://doi.org/10.17221/3294-vetmed.

Vallejos-Vidal, E., Reyes-López, F., Teles, M., & MacKenzie, S. (2016). The response of fish to immunostimulant diets. *Fish & Shellfish Immunology*, *56*, 34–69. https://doi.org/10.1016/j.fsi.2016.06.028.

Wang, K., Luo, C., Liu, H., Xu, J., Sun, W., & Zhou, L. (2012). Nematicidal activity of the alkaloids from *Macleaya cordata* against certain nematodes. *African Journal of Agricultural Research*, *7*(44), 5925-5929. https://doi.org/10.5897/AJAR11.1940.

Wianowska, D., & Gil, M. (2019). Critical approach to PLE technique application in the analysis of secondary metabolites in plants. *Trends in Analytical Chemistry*, *114*, 314–325. https://doi.org/10.1016/j.trac.2019.03.018.

Xavier, M. J., Conceição, L. E. C., Valente, L. M. P., Colen, R., Rodrigues, A. C. M., Rocha, R. J. M., Custódio, L., Carballo, C., Manchado, M., & Engrola, S. (2021). Dietary natural plant extracts can promote growth and modulate oxidative status of Senegalese sole postlarvae under standard/challenge conditions. *Animals*, *11*(5), 1398. https://doi.org/10.3390/ani11051398.

Xavier, M. J., Engrola, S., Conceição, L. E. C., Manchado, M., Carballo, C., Gonçalves, R., Colen, R., Figueiredo, V., & Valente, L. M. P. (2020). Dietary antioxidant supplementation promotes growth in Senegalese Sole post larvae. *Frontiers in Physiology*, *11*. https://doi.org/10.3389/fphys.2020.580600.

Yousefi, M., Ghafarifarsani, H., Hoseinifar, S. H., Rashidian, G., & Doan, H. V. (2021). Effects of dietary marjoram, *Origanum majorana* extract on growth performance, hematological, antioxidant, humoral and mucosal immune responses, and resistance of common carp, *Cyprinus carpio* against *Aeromonas hydrophila*. *Fish & Shellfish Immunology*, *108*, 127–133. https://doi.org/10.1016/j.fsi.2020.11.019.

Zaynab, M., Fatima, M., Abbas, S., Sharif, Y., Umair, M., Zafar, M. M., & Bahadar, K. (2018). Role of secondary metabolites in plant defense against pathogens. *Microbial Pathogenesis*, *124*, 198–202. https://doi.org/10.1016/j.micpath.2018.08.034.

Zhou, S., Li, W. X., Wang, Y. Q., Zou, H., Wu, S. G., & Wang, G. T. (2017). Anthelmintic efficacies of three common disinfectants and extracts of four traditional Chinese medicinal plants against *Gyrodactylus Kobayashii* (monogenea) in goldfish (*Carassius auratus*). *Aquaculture*, *466*, 72–77. https://doi.org/10.1016/j.aquaculture.2016.09.048.

Zhu, Z., Wen, Y., Yi, J., Cao, Y., Liu, F., & McClements, D. J. (2019). Comparison of natural and synthetic surfactants at forming and stabilizing nanoemulsions: Tea saponin, *Quillaja saponin*, and Tween 80. *Journal of Colloid and Interface Science*, *536*, 80–87. https://doi.org/10.1016/j.jcis.2018.10.024.

Zoral, M. A., Futami, K., Endo, M., Maita, M., & Katagiri, T. (2017). Anthelmintic activity of *Rosmarinus officinalis* against *Dactylogyrus minutus* (Monogenea) infections in *Cyprinus carpio*. *Veterinary Parasitology*, *247*, 1–6. https://doi.org/10.1016/j.vetpar.2017.09.013.