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Review

Medicinal plants and their applications in shrimp culture

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ABSTRACT. Aquaculture has increasingly focused on plants due to their ability to promote growth and combat diseases through their antimicrobial, anti-inflammatory, and antioxidant properties. Additionally, plants are highly nutritious, stimulate the immune system, and enhance appetite. Herbal compounds have been shown to inhibit or block virus transcription, reducing replication in host cells and improving nonspecific immunity. They also have the advantage of being derived from various parts of the plant and can be used in multiple forms, such as extracts, supplements, and powder. Combined with fishmeal or polysaccharides, these compounds can improve hematological parameters, performance metrics, and growth. Furthermore, plant species' active principles can stimulate digestive enzyme secretion, enhancing growth and survival. Medicinal plant compounds also include components that can induce the reproduction of crustaceans. Therefore, understanding the metabolic and immunological mechanisms of phytochemical-crustacean interactions is essential to clarify the organism's response and the effectiveness of the applied compounds.

Keywords: diseases; virus; bacteria; crustaceans; aquaculture

INTRODUCTION

Aquaculture has become the main source of aquatic food worldwide. In 2022, farming of aquatic animals surpassed for the first time capture fisheries, consolidating its contribution to human nutrition, providing more than 57% of aquatic animal foods (FAO 2024). It is estimated that as the world's human population grows, this activity will continue to increase. For its continued development and progress, large-scale aquaculture uses synthetic chemicals to increase breeding productivity, increase larval survival, improve feed efficiency, reduce stress during transport of organisms, control pathogens, and combat epiphytes and adherent organisms that degrade water quality (Thazeem et al. 2022). However, the application of synthetic chemicals negatively impacts the environment and animal and human health due to their toxicity (Thazeem et al. 2022). Consequently, alternatives need to be sought to mitigate these adverse effects.

One of the alternatives in aquaculture is the use of plants, mainly those it has been proven to control diseases due to their antioxidant and antimicrobial activities (Citarasu 2010, Hu et al. 2014, Ghosal & Chakraborty 2014, Gabriel et al. 2015). In addition to the fact that plants have antibacterial, antiviral, antiparasitic (protozoan, monogenean), and antioxidant abilities, it has been shown that plant products can stimulate appetite, promote growth performance, act as immunostimulant agents, and induce reproductive maturation since aphrodisiac properties are attributed (Citarasu 2010, Chakraborty & Hancz 2011).

The use of medicinal plants in aquaculture becoming the goal of active scientific research in countries such as Egypt (Goda 2008, Aly & Mohamed 2010, Ahmad & Abdel-Tawwab 2011, Abdel-Tawwab 2012), Japan

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(Takaoka et al. 2011), India (Sivaram et al. 2004), Indonesia (Caruso et al. 2013), Iran (Mousavi et al. 2011), South Korea (Harikrishnan et al. 2010, 2011a), and Mexico (De Ocampo & Jiménez 1993). Common studies on applying specific plants are grounded in traditional knowledge or folklore, passed down through generations, and associated with particular geographic regions.

Studies demonstrate the direct stimulatory effects of numerous phytobiotics or herbal extracts on the immune systems of fish and shrimp (Vallejos-Vidal et al. 2016). These activities are primarily attributed to bioactive compounds such as phenols, sulfur-containing compounds, terpenoids, alkaloids, flavonoids, and saponins (Citarasu 2010, Chakraborty & Hancz 2011). Consequently, phytochemicals can be considered viable alternatives to chemical treatments in aquaculture (Sivaram et al. 2004, Kirubakaran et al. 2010).

This article reviews the use of medicinal plants in the cultivation of crustaceans, bringing together information on the various plants applied to different species of crustaceans of commercial interest.

Metabolites extracted from plants of interest in aquaculture

Plants produce a variety of bioactive compounds to tolerate their habitats, unfavorable weather conditions, protection against predators, pathogens, or environmental stress, insect attraction to promote pollination (Harborne 1984, Mendoza & Escamilla 2016, Varijakzhan et al. 2020). These organisms have two metabolisms: the primary metabolism, present in all plants and performing essential functions, is where most of the carbon, nitrogen, and energy are incorporated into common molecules found in all cells, such as amino acids, nucleotides, sugars, and lipids, which are necessary for the functioning of the organisms (Mendoza & Escamilla 2016), and the secondary metabolism that allows them to produce and accumulate compounds of various chemical natures. The synthesis of secondary metabolites depends on the plant's development stage. Its constitutive levels only increase as part of the response to abiotic or biotic stress (Sepúlveda et al. 2003). They are located or concentrated mainly in the leaves, stems, flowers, roots, bark, fruits, and seeds, depending on the family of the species (Lallianrawna et al. 2013).

Within these bioactive compounds, several groups stand out: nitrogen and sulfur compounds: cyanogenic glycosides, glucosinate (Taiz & Zeiger 2005); alkaloids: benzylisoquinoline, tropane, pyrrolizidine or purinic alkaloids (Kennedy & Wightman 2011); phenols: simple phenols, acidic phenols, acetophenones, phenylacetic acids, hydroxycinnamic acids, coumarins, flavonoids, biflavonyls, benzophenones, xanthones, stilbenes, quinones and betacyanins, lignans, neolignans, tannins and flobaphenes gallic acid, butein, hydroquinone, catechol, eugenol (Davin & Lewis 2000); terpenes: hemiterpene; monoterpenes, sesquiterpenes, diterpenes, sesterpenes, triterpenes and tetraterpenes (Gershenzon & Croteau 2012); saponins: triterpenoids, steroids or steroid glycoalkaloids (Güçlü-Üstündağ & Mazza 2007).

Aquaculture has fixed its attention on plants due to their ability to promote growth and to be effective against diseases, for their antimicrobial, anti-inflammatory, and antioxidant properties; moreover, because they are highly nutritious (Direkbusarakom 2004, Ng'ambi et al. 2016, Yilmaz et al. 2018). These benefits arise from its bioactive compounds (Awad & Awaad 2017), and due to these properties, there is the possibility of using compounds in the form of steroids with a physiological effect similar to the steroid hormone, establishing the use of more than 50 herbs in aquaculture with a biological effect such as immune system stimulants (Minomol 2005, Citarasu et al. 2006), growth rate promoters (Goda 2008), stimulating appetite by increasing consumption (Kim et al. 1998, Venketramalingam et al. 2007), gonad maturation inducers (Liñán-Cabello et al. 2004), antifertility agent (Ghosal & Chakraborty 2014, Gabriel et al. 2015), antimicrobial agent (Chitmanat et al. 2005), and anti-stress agent (Ardó et al. 2008, Hsieh et al. 2008).

Medicinal plants and aquaculture

Although man has used medicinal plants since ancient times, being instinctive at first, there was no information about how to use them for healing purposes. Therefore, its applications were initially based on particular experiences until specific medicinal plants attributions for treating certain diseases were discovered, leaving aside their uses empirically and based on explicit facts (Kelly 2009). Medicinal plants comprise a diversity of herbs and plants, and compounds derived from them are components of traditional medicine and the main source for developing and synthesizing new medicines (Asimi & Sahu 2013, Singh 2015).

The vast majority of research on the use of medicinal plants in aquaculture focused on the identification of biological activity and not on the determination of the natural product (Ji et al. 2012), to better understand its form of action (Reverter et al. 2014). However, others emphasize that exploratory studies on the potential of medicinal plants in aquaculture may be misleading due to using the wrong part or solvent (Reverter et al. 2014). In addition, an important point is using the appropriate dose to obtain the desired effects because wrong doses have presented toxic effects (Kavitha et al. 2012). The great advantage of using plants is that they can be applied in parts (seed, leaf, root) or whole, in the form of raw or purified extracts, extracted compounds, additives in the diet, aqueous solution, either in isolation or as a combination of extracts, mixed with other imunostimulants, prebiotics or probiotics (AftabUddin et al. 2017, Liao et al. 2022). A fact to highlight is that even when medicinal plants continue to be tested, many of their mechanisms of action and toxicity have not yet been well understood, which makes additional studies necessary to allow their safe use in aquaculture. It is, therefore, necessary to carry out *in vivo* tests to determine biological activity, identification, and phytochemical characteristics and to carry out cytotoxicity tests *in vitro* tests to help elucidate the effects of bioactives on the physiology of the organisms in which they are applied and survival against various pathogenic infections in the organisms studied.

Medicinal plants and crustaceans

Viral diseases

One of the problems that aquaculture has as it becomes intensive is the incidence of diseases, including various infectious diseases, generating serious damage and significant economic losses (Citarasu 2012), becoming one of the limiting factors for the growth of aquaculture (Assefa & Abunna 2018). Using medicinal plants as antimicrobials in aquaculture has generated a growing worldwide interest (Van Hai 2015, Dey et al. 2020). In this sense, various herbal extracts have been shown to successfully control viruses in shrimps, such as the white spot syndrome virus (WSSV) and yellow head virus, both *in vitro* and *in vivo* (Velmurugan et al. 2012).

Plants are considered an alternative for combating diseases because of their longstanding use as home remedies for humans and animals worldwide. Some bioactive compounds in plants can inhibit or block viral transcription, thereby reducing replication within host cells and enhancing nonspecific immunity (Sivasankar et al. 2015).

In the case of *Penaeus vannamei*, multiple medicinal plants that have been used against viruses, plants such as *Callophyllum inphyllum*, *Clinacanthus nutans*, *Ocimium sanctum*, *Phyllanthus acidus*, and *Tinospora crypt*, have been shown to have effects against the yellow head shrimp virus (Prieto et al. 2005). Likewise, ethanolic extracts (1, 2, and 4%) of *Uncaria tomentosa* were tested against WSSV in the species (Júnior et al. 2018). Likewise, the biochemical, hematological, and immunological impacts of extracts of olive leaf (*Olea europaea*) were investigated in *P. vannamei* experimentally infected by the WSSV, demonstrating its effectiveness (Gholamhosseini et al. 2020).

In the species, *Fenneropenaeus indicus* (*Pennaeus indicus*), a wide variety of plants such as *Aegle marmelos*, *Agathi grandiflora*, *Allium sativum*, *Aristolochia indica*, *Azadirachta indica*, *Cassia fistula*, *Catharanthus roseus*, *Curcuma longa*, *Cynodon dactylon*, *Emilia sonchifolia*, *Lantana camara*, *Melia azedarach*, *Mimosa pudica*, *Momordica charantia*, *Morus alba*, *Ocimum americanum*, *Phyllanthus amarus*, *P. emblica*, *Psidium guajava*, *Solanum nigrum*, *Tridax procumban*, and *Tylophora indica* were used against viral infections (Balasubramanian et al. 2007, Bindhu et al. 2014, Maikaeo et al. 2015), proven that herbal antiviral compounds are able not only to control viral pathogens but also to stimulate the immune system against pathogenic infections (Citarasu 2012).

In turn, five herbs (*Adathoda vasica*, *A. grandiflora*, *Leucas aspera*, *Psoralea corylifolia*, and *Quercus infectoria*) were applied to detect antiviral activity and efficacy against WSSV using different polar and non-polar organic solvents (hexane, ethyl acetate, methanol) (Bindhu et al. 2014). In the shrimp *Penaeus monodon*, plants such as *Acalypha indica*, *C. dactylon*, *Picrorrhiza kurrooa*, *Withania somnifera*, and *Zingiber officinali*s, were used for their antiviral activity against the yellow head virus (Yogeeswaran et al. 2012).

Herbal compounds can act as immunostimulants for the host immune system. They can inhibit or block the transcription of viruses, reducing replication in host cells and improving nonspecific immunity (Citarasu 2012).

Bacterial diseases

Antibiotics have long been applied in the search for solutions to control diseases (Verschuere et al. 2000). Still, the excessive use of these medicines by inexperienced aquaculture producers promotes an increase in the mortality rate in sick aquatic animals and additionally increases water contamination (Watts et al. 2017, Liao et al. 2022). Studies have shown that antibiotics accumulate in the cultivation environment, sediments, in animal tissues, generating consequences for human and environmental health which has made aquaculturists seek natural options (Holmström et al.

2003, Boxall et al. 2004, Goldburg & Naylor 2005, Naylor & Burke 2005, Uddin & Kader 2006, Sapkota et al. 2008, Heuer et al. 2009, Shimizu et al. 2013).

The wide use of antibiotics has led to the development of resistant bacterial strains since large amounts of antimicrobial compounds have been used in the systems (Jacoby 2017). The emergence of diseases creates problems for producers because the consumption of shrimp can also cause diseases in humans by *Clostridium botulinum*, *Escherichia coli*, *Salmonella enterica*, *Staphylococcus aureus*, *Vibrio cholerae*, and *V. parahaemolyticus*, that contaminate fresh shrimp (Sánchez-Ortega et al. 2014).

Specifically, the bacteria of the genus *Vibrio* cause strong mortalities and economic losses in shrimp cultivation (Santiago et al. 2009). This genus includes at least 100 recognized species. It includes the main bacterial pathogens for aquaculture, such as *V. anguillarum*, *V. fischeri*, *V. harveyi*, (Silvester et al. 2017), and *V. parahaemolyticus*, which stands out for being the main pathogen in current crops, cause diseases such as early mortality syndrome (EMS), also called acute necrotizing hepatopancreatitis (AHPND) (Williams et al. 2017). Conventional antibiotics such as florfenicol and enrofloxacin were tested to combat vibriosis, and the results were variable (Cuellar 2013). However, the appearance of antimicrobial resistance in bacterial strains is directly related to antibiotics that led to resistance (Banerjee et al. 2013), so natural alternatives such as plants have been sought to invest against these diseases (Table 1).

Among the efforts to combat vibriosis, stand out works with plants against *V. harveyi* in tiger shrimp *P. monodon*. An example of this is the extract of *Solanum nigrum* with doses of 0.1 and 1.0% that demonstrated action as an immunostimulant, producing a positive effect by increasing resistance to the disease by improving the immune response (Harikrishnan et al. 2011b) as well as the application of extracts of *A. ilicifolius*, which inhibited the growth of *V. harveyi* (Saptiani et al. 2017). In addition, studies were conducted with extracts in different concentrations of a mixture of *Aloe vera*, *Allium cepa*, *Andrographis pariculata*, *Annona squamosa*, *A. indica*, *Citrus aurantifolia*, *Coriandrum sativum*, *Ocimum sanctum*, and *P. guajava* in the diets of marine shrimp *P. monodon* against *V. harveyi*, being more efficient against this bacterium (AftabUddin et al. 2017). Similarly, extracts of 21 herbs were applied to inhibit the activity of *V. alginolyticus*; being *A. sativum*, *Emblica officinalis*, and *Syzygium aromaticum* the plants that strongly inhibited the growth of the bacterium *in vitro* conditions, while under *in vivo* conditions, ethyl acetate extracts of *A. sativum* and *E. officinalis* and successfully controlled the disease in shrimp at doses of 10 mg g^{-1} of feed, highlighting that this study was the first for the molecular identification and biocontrol of *V. alginolyticus* in shrimps in Bangladesh (Abdul-Hannan et al. 2019).

In the case of shrimp *P. vannamei*, acetonic, ethanolic, methanolic, and aqueous extracts of the leaves of the aromatic plant with medicinal properties, *Eucalyptus camaldulensis*, have been used as anti-bacterial agents, species of *V. azureus* and *V. harveyi* (Ghasemian 2018). In addition, herbs of traditional Chinese medicine with proven antibacterial ability, such as *Artemisia argyi*, *Astragalus membranaceus*, *Atractylodis macrocephalae*, *Cortex moutan*, *C. phellodendri*, *Cistanche deserticola*, *Eucommia ulmoides*, *Flos lonicerae*, *Fructus forsythia*, *F. mume*, *Galla chinensis*, *Houttuynia cordata*, *Isatidis radix*, *Polyporus umbellatus*, *Radix bupleuri*, *R. glycyrrhizae*, *R. sophorae*, *Rheum officinale*, *Rhizoma coptidis*, *R. cyrtomii*, *Scutellaria baicalensis*, *Terminalia chebula*, and *Wolfiporia extensa*, were applied positively against *V. harveyi* (Pan & Yan 2020) and *Allium sativum* and *Matricaria chamomilla*, against *V. parahaemolyticus* (Chirawithayaboon et al. 2020, Abdel-Tawwab et al. 2022), while polysaccharides of aqueous origin of *Angelica sinensis* and aqueous extracts of *Theobroma cacao* were tested against *V. alginolyticus* in the species (Pan et al. 2018, Lee et al. 2020) noting that the two extracts were effective against the pathogen.

On the other hand, in the species *Macrobrachium amazonicum*, investigations were carried out on the antimicrobial potential of stem extracts, leaves, flowers, fruits, and seeds of *Moringa oleifera* against *Vibrio* spp. (*V. cholerae*, *V. vulnificus*, *V. mimicus*) the ethanolic extracts of the fruits are effective against the different species of *Vibrio* (Nogueira-Brilhante et al. 2015).

An emerging new bacterial disease, AHPND, is the cause of mass mortality in shrimp *P. vannamei*. Extracts of the seed of *Rhodomyrtus tomentosa* were tested to determine the antibacterial effect against strains of AHPND *in vitro* (*V. parahaemolyticus* [VPAHPND] KC12.020, VPAHPND KC13.14.2] and *V. harveyi* [KC13.17.5]) showing that it can help reduce this disease (Dang et al. 2019). On the other hand, against *Lactococcus garvieae*, aqueous extracts from the leaves of *Eichhornia crassipes* were tested, being incorporated into the diet of the freshwater shrimp *Macrobrachium rosenbergii* as an immunostimulant, proving that it can complement diets and improve the

Table 1. Medicinal plants used to control *Vibrios* spp. in the cultivation of crustaceans.

Medicinal plant	Pathogen	Reference
Acanthus ilicifolius	*Vibrio harveyi*	Saptiani et al. (2017)
Allium cepa		AftabUddin et al. (2017)
Allium sativum		Abdul-Hannan et al. (2019)
Allium sativum		Chirawithayaboon et al. (2020)
Allium sativum	*Vibrio vulnificus*	Nogueira-Brilhante et al. (2015)
Aloe vera		AftabUddin et al. (2017)
Andrographis pariculata		AftabUddin et al. (2017)
Angelica sinensis		Pan et al. (2018)
Annona squamosa		AftabUddin et al. (2017)
Artemisia argyi		Pan & Yan (2020)
Astragalus membranaceus		Pan & Yan (2020)
Atractylodis macrocephalae		Pan & Yan (2020)
Azadirachta indica		AftabUddin et al. (2017)
Cistex phellistanche		Pan & Yan (2020)
Citrus aurantifolia		AftabUddin et al. (2017)
Coriandrum sativum		AftabUddin et al. (2017)
Cortex moutan		Pan & Yan (2020)
Cortex phellodendri		Pan & Yan (2020)
Emblica officinalis	*Vibrio alginolyticus*	Abdul-Hannan et al. (2019)
Eucalyptus camaldulensis		Ghasemian (2018)
Eucalyptus camaldulensis	*Vibrio azureus*	Ghasemian (2018)
Eucommia ulmoides		Pan & Yan (2020)
Flos lonicerae		Pan & Yan (2020)
Fructus forsythia		Pan & Yan (2020)
Galla chinensis		Pan & Yan (2020)
Houttuynia cordata		Pan & Yan (2020)
Isatidis radix		Pan & Yan (2020)
Matricaria chamomilla	*Vibrio parahaemolyticus*	Abdel-Tawwab et al. (2022)
Moringa oleifera	*Vibrio cholerae*	Nogueira-Brilhante et al. (2015)
Ocimum sanctum		AftabUddin et al. (2017)
Polyporus umbellatus		Pan & Yan (2020)
Radix bupleuri		Pan & Yan (2020)
Radix glycyrrhizae		Pan & Yan (2020)
Radix sophorae		Pan & Yan (2020)
Rheum officinale		Pan & Yan (2020)
Rhizoma coptidis		Pan & Yan (2020)
Rhizoma cyrtomii		Pan & Yan (2020)
Rhodomyrtus tomentosa		Dang et al. (2019)
Rhodomyrtus tomentosa		Dang et al. (2019)
Scutellaria baicalensis		Pan & Yan (2020)
Solanum nigrum		Harikrishnan et al. (2011b)
Syzygium aromaticum		Abdul-Hannan et al. (2019)
Syzygium aromaticum		Nogueira-Brilhante et al. (2015)
Terminalia chebula		Pan & Yan (2020)
Theobroma cacao		Lee et al. (2020)

immune resistance capacity of shrimp (Chang et al. 2013).

The use of plants against these diseases is because phytobiotics exhibit antibacterial activities by their nature (polysaccharides, phenolics, proteoglycans, and flavonoids), which play an important role in the prevention or control of infectious microbes (Citarasu 2010, Chakraborty & Hancz 2011); mainly by various mechanisms, including alteration of the bacterial cell wall, improvement of lysozyme and complement activity, translation of nucleic acids and blocking of transcription (Ma et al. 2018).

Stimulation in growth

The use of plants in animal nutrition has great potential, possibly because they serve as substitutes for growth promoters due to their positive effects on digestion, intestinal microbiota, and health (Sutili et al. 2017). The basis of the application of plants as food is the fact that they are a source of nutrients such as amino acids, carbohydrates, minerals, and vitamins (Sivaram et al. 2004, Xie et al. 2008, Jeney et al. 2009, Mustafa et al. 2017, Kalaiselvi et al. 2018). All ingredients that play a role in increasing growth rate (Babaheydari & Heyrati 2014) accelerate metabolism and improve enzymatic activity in the digestive tract (Lin et al. 2006) for the digestive process to become more effective, resulting in greater growth (Van Hai 2015). Several studies show that plant extracts stimulate appetite and promote weight gain when administered to cultivated species (Pavaraj et al. 2011, Takaoka et al. 2011, Genovese et al. 2012) (Table 2).

Plants have been used in various forms (parts that make them up, extracts, supplements, powders, combined with fishmeal or polysaccharides) as alternative methods in feeding and to determine their effectiveness, hematological parameters, disease prevention, parameters of performance and growth (Munaeni et al. 2019). Studies have shown that they synergize the growth performance and physiological state of *P. vannamei*, one of the economically valuable aquaculture products, but face problems due to diseases and growth. In addition, the growth-promoting effects of plants can be due to their various active compounds, leading to more positive effects on digestion, absorption, and assimilation of nutrients (Srinivasan 2005, Azeez 2008, Yılmaz et al. 2018). Among the species widely applied to determine their effects on the growth of *P. vannamei* are *Astagalus membranaceus*, *Bidens alba*, *Codonopsis pilosula*, *Glycyrrhiza uralensis*, *Jatropha curcas*, *Morinda citrifolia*, *Phyllanthus amarus*, *Plectranthus amboinicus*, and *P. guajava* (Huang et al. 2017, Prathomya et al. 2019, Ngo et al. 2020, Dewi et al. 2021, Moh et al. 2021, Huang et al. 2022). Additionally, it was reported that the supplementation of the *P. vannamei* postlarvae diet with *M. citrifolia* fruit extract (Noni) successfully increased shrimp growth (body weight and total length) and growth yields (specific growth rate, average daily growth, food conversion rate, and condition factor) (Moh et al. 2021).

On the other hand, plants such as *Cyanodon dactylon* and *Zingiber officinale* and have been used as food for freshwater shrimp *M. rosenbergii*, producing an increase in growth parameters (mean body weight, average body length, specific growth rate, condition factor, weight gain rate, length gain rate, and feed conversion rate) (El Desouky et al. 2012). Similarly, *Alternanthera sessilis*, *A. paniculata*, *Cissus quadrangularis*, *C. sativum*, *Eclipta alba*, *Glycyrrhiza glabra*, *Melaleuca alternifolia*, *Menthe arvensis*, *Murraya koenigii*, *Myristica fragrans*, *Ocimium sanctum*, *Piper longum*, *P. nigram*, *Quercus infectoria*, *Withania somnífera*, and *Zingiber officinale* have been reported to improve growth and survival weight, protein index and specific growth efficiency rate in *M. rosenbergii* (Bhavan et al. 2011, 2012, 2013a,b, Shanthi et al. 2012, Radhakrishnan et al. 2013, Liu et al. 2021). *O. sanctum*, *Phyllanthus amarus*, and *Solanum trilobatum* have been used as a diet to determine growth performance, muscle biochemical components, amino acids, and fatty acid compositions of *M. rosenbergii* (Muralisankar et al. 2016), noting significant improvements in survival, nutritional indexes (weight gain, specific growth rate, and protein efficiency index), muscle biochemical constituents (total proteins, amino acids, carbohydrates and lipids) essential amino acid and fatty acid profiles of shrimps fed with incorporated herbal feed.

In freshwater shrimp *Macrobrachium malcolmsonii*, the effects of medicinal herbs *Alternanthera sessilis*, *Cissus quadrangularis* and *Eclipta alba*, on growth performance, digestive enzymes, and biochemical components were studied, finding that at the end of the experiments, shrimp survival improved significantly in plant-based foods. In addition, growth parameters such as weight gain, specific growth rate, and protein efficiency rate were significantly higher in groups fed herbal diets compared to control (no herbs) (Radhakrishnan et al. 2014).

In the species *P. indicus*, plants were applied in their diet, enriched in the first instance nauplii of *Artemia* with plant extracts such as *A. paniculata*, *Hygrophila spinosa*, *Psoralea corylifolia*, *Solanum trilobatum*, *W. somnifera* and *Zingiber officinale* (Citarasu et al. 2002, 2003), and *Leucas aspera*, *Manihot esculenta*, *Phyllanthus niruri* and *Ricinus communis* (Immanuel et al. 2004), improving the nutritional indices of shrimp. Herbal extracts such as *Adhatoda vasica*, *Murraya koenigii*, *Ocimum basilicum*, *Psoralea corylifolia*, and *Quercus infectoria* incorporated in artificial feed have also been tested to improve weight gain and specific growth rate in shrimp significantly (Velmurugan & Citarasu 2010).

One of the species widely used in aquaculture, *P. monodon*, has been carried out several studies with plants as growth promoters. Dietary extracts of *Forsythia*

Table 2. Summary of plants used for the growth of various crustaceans.

Plant	Crustacea	Reference
Andrographis paniculata	*Penaeus indicus*	Citarasu et al. (2003)
Adhatoda vasica		Velmurugan & Citarasu (2010)
Aegle marmelos	*Penaeus monodon*	Citarasu et al. (2006)
Aloe vera		AftabUddin et al. (2017)
Alternanthera sessilis	*Macrobrachium malcomnsonii*	Radhakrishnan et al. (2014)
Alternanthera sessilis	*Macrobrachium rosenbergii*	Radhakrishnan et al. (2013)
Andrographis paniculata		Shanthi et al. (2012)
Andrographis paniculata		AftabUddin et al. (2017)
Annona squamosa		AftabUddin et al. (2017)
Astagalus membranaceus	*Penaeus vannamei*	Huang et al. (2017), Prathomya et al. (2019)
Azadirachta indica		AftabUddin et al. (2017)
Bidens alba		Huang et al. (2022)
Cissus quadrangularis		Radhakrishnan et al. (2014)
Cissus quadrangularis		Shanthi et al. (2012), Radhakrishnan et al. (2013)
Citrus aurantifolia		AftabUddin et al. (2017)
Codonopsis pilosula		Prathomya et al. (2019)
Coriandrum sativum		Bhavan et al. (2012)
Coriandrum sativum		AftabUddin et al. (2017)
Cyanodon dactylon		El Desouky et al. (2012)
Cyanodon dactylon		Citarasu et al. (2006)
Eclipta alba		Radhakrishnan et al. (2014)
Eclipta alba		Shanthi et al. (2012), Radhakrishnan et al. (2013)
Eclipta alba		Citarasu et al. (2006)
Emblica officinalis		Chandran et al (2016)
Forsythia suspensa		Yin et al. (2008)
Glycyrrhiza glabra		Bhavan et al. (2013a)
Glycyrrhiza uralensis		Prathomya et al. (2019)
Hygrophila spinosa		Citarasu et al. (2002)
Jatropha curcas		Rodríguez-González et al. (2018)
Leucas aspera		Immanuel et al. (2004)
Manihot esculenta		Immanuel et al. (2004)
Melaleuca alternifolia		Liu et al. (2021)
Melastoma malabathricum	*Penaeus pelagicus*	Alam et al. (2019)
Menthe arvensis		Bhavan et al. (2012)
Morinda citrifolia		Moh et al. (2021)
Murraya koenigii		Velmurugan & Citarasu (2010)
Murraya koenigii		Bhavan et al. (2012)
Myristica fragrans		Bhavan et al. (2013a)
Ocimum basilicum		Velmurugan & Citarasu (2010)
Ocimum sanctum		Bhavan et al. (2011), Muralisankar et al. (2016)
Ocimum sanctum		AftabUddin et al. (2017), Chandran et al. (2016)
Ollium cepa		AftabUddin et al. (2017)
Phyllanthus amarus		Ngo et al. (2020)
Phyllanthus amarus		Muralisankar et al. (2016)
Phyllanthus niruri		Immanuel et al. (2004)
Picrorhiza kuroa		Citarasu et al. (2006)
Piper longum		Bhavan et al. (2013b)
Piper nigram		Bhavan et al. (2013b)
Plectranthus amboinicus		Huang et al. (2022)
Psidium guajava		Dewi et al. (2021)
Psidium guajava		AftabUddin et al. (2017)
Psoralea corylifolia		Citarasu et al. (2002)
Quercus infectoria		Velmurugan & Citarasu (2010)
Quercus infectoria		Bhavan et al. (2013a)

Continuation

Plant	Crustacea	Reference
Ricinus communis		Immanuel et al. (2004)
Solanum trilobatum		Citarasu et al. (2003)
Solanum trilobatum		Muralisankar et al. (2016)
Tinospora cordifolia		Citarasu et al. (2006), Chandran et al. (2016)
Withania somnífera		Citarasu et al. (2002)
Withania somnífera		Bhavan et al. (2011)
Withania somnífera		Chandran et al. (2016)
Zingiber officinalis		Citarasu et al. (2002)
Zingiber officinalis		El Desouky et al. (2012), Bhavan et al. (2013b)

suspensa were made to determine the effects on growth performance, where the results showed that growth performance (final wet body weight, weight gain, biomass gain) in shrimps fed with extracts of the flat was higher than that of shrimps fed basal diet (without extract) (Xie et al. 2018). Similarly, ethanolic extracts of *Aegle marmelos*, *Cyanodon dactylon*, *Eclipta alba*, *Picrorhiza kuroa*, and *Tinospora cordifolia*, were incorporated into the feed of *P. monodon*, producing a significant gain in biochemical components (Citarasu et al. 2006). In the same vein, extracts of petroleum ether, methanol and N-hexane from the plants *A. indica*, *A. paniculata*, *A. squamosa*, *A. vera*, *C. aurantifolia*, *C. sativum*, *Ollium cepa*, *O. sanctum*, and *P. guajava* have been used to study their effects on growth and survival rate, observing that the shrimp fed with doses of methanolic extractions of 2.5 mL kg^{-1} showed higher survival rate, specific growth rate and better feed conversion rate compared to the other groups (AftabUddin et al. 2017). Polyherbal formulas of *Emblica officinalis*, *Ollium sanctum*, *Tinospora cordifolia*, and *Withania somnifera*, have also been used as potential growth promoters of shrimp *P. monodon*, improving growth performance, feed conversion efficiency, and feed conversion rate (Chandran et al. 2016).

Similarly, the effect of the aqueous extract of the leaf of *Melastoma malabathricum* on the growth of the crab *Portunus pelagicus* was evaluated, showing that doses of extract of 15 µg g^{-1} of body weight increase the growth of the crab (Alam et al. 2019).

The various investigations show a higher activity of digestive enzymes when plants are used in the diets of cultured shrimp, indicating that they are a good appetizer. This is probably determined by the active principles of the plant species employed, which stimulate the secretion of digestive enzymes, resulting in better use of food, which ultimately produces better growth and survival.

Stimulating sexual maturation and inducing reproduction

Hormonal control of reproduction has been studied in many species of crustaceans, such as river crabs, shrimps, crabs, lobsters, etc. It has been observed that various hormones of the neuroendocrine organs play an essential role in controlling gonadal maturation (Laufer et al. 1993, Fingerman 1997, Chang et al. 2001, Nagaraju 2007, Mazurová et al. 2008, Raviv et al. 2008). Alternative methods of ablation to induce maturation have emerged. For example, a diet based on natural foods, such as mollusks, squid, and polychaetes, commonly promotes shrimp farmers' reproductive performance (Meunpol et al. 2007). Still, these foods can often cause pathogenic contamination in shrimp reproduction. This fact has led to applying plants as an inductive method of reproduction of these organisms (Citarasu et al. 2002).

Medicinal plant compounds include phytoestrogens such as isoflavonoids (flavonoids and isoflavones), cholesterol, lignano (Lehtinen & Lehtinen 2001), anthraquinone (Matsuda et al. 2001), chalcone (Rafi et al. 2000), and saponin (Chan et al. 2002). Phytoestrogens have a similar structure to the steroid hormone estradiol (E2) in animals (Lehtinen & Lehtinen 2001). It has been pointed out that they have the same effect as estrogens that influence the reproductive process, stimulating and inhibiting the reproduction process (Tsai et al. 2000, Trant et al. 2001, Andersen et al. 2003). Due to their low molecular weight, they can easily cross cell membranes and bind to estrogen receptors (REs), triggering an estrogenic or antiestrogenic effect (Lehtinen & Lehtinen 2001, Ososki & Kennelly 2003). The estrogenic or antiestrogenic effect in animals will depend on the relationship between endogenous estrogen, aromatase activity, species, reproductive status, duration of exposure, and method of administration (oral or parenteral) (Rocha-Monteiro et al. 2000, Bennetau-Pelissero et al. 2001, Green & Kelly 2009).

In commercial species such as *Penaeus merguiensis*, research has been carried out to increase reproductive maturation due to decreased production due to the increasing capture of wild shrimp for consumption, which led to the test with extracts of dichloromethane and acetone of *Emilia sonchifolia* for stimulation of ovarian development (Maikaeo et al. 2015) thanks to its content of alkaloids, tannins (Cheng & Röder 1986), flavonoids (Srinivasan & Subramanian 1980), sterols, palmitic acid and honey acid (Gao et al. 1993). Even the application of plants in the reproductive aspect is being extended to shrimp species with commercial potential, such as the shrimp *P. merguiensis*. However, seed production of this species currently presents an inadequate supply of good mature males in quality and quantity, given its dependence mainly on wild breeders (Memon et al. 2012). Studies are being carried out for the preservation of its germplasm, applying extracts of *Moringa oleifera* and ginger (*Zingiber officinale*) in refrigerated spermatophores in which supplementation with the mentioned extract resulted in a significant increase in sperm survival concerning control and without spermicidal effect (Nimrat et al. 2020).

A method used to accelerate gonadal maturity in shrimps of the species *P. vannamei* is the supply of foods with high cholesterol content, such as the plant *Melasthoma malabatrhicum*, which is commonly used as a medicine because it has a metabolic compound consisting of saponin, tannin, triterpenoid/steroid and flavonoid, lanosterol, vegetable cholesterol that is considered a precursor hormone of the maturation process of the gonads in white shrimps (Wouters et al. 2001). Similarly, this plant has been used as an inducer to accelerate the maturation of the ovary of the crab *Scylla olivacea* (Farizah et al. 2016, 2018).

Babu et al. (2008) observed an increase in fertility (42%) and gonad weight (38%), a reduction in the period between seedlings, and a better quality of *P. monodon* larvae hatched when fed with *Artemia* previously enriched with a diet of herbs such as *Ferula asafoetida*, *Mucuna prurita*, *Piper longum* and *W. somnifera*. Seeking to test new strategies to improve the male reproductive performance of cultured shrimps, especially those aimed at reducing melanization, which causes deterioration of the reproductive tract, evaluated the effect of a fresh food supplementation with pollen and paprika on spermatophores and sperm quality of *Farfantapenaeus paulensis*, finding a higher sperm count, melanization, and that paprika supplementation did not affect spermatophores or sperm quality (Braga et al. 2013).

CONCLUSION

Phytochemical compounds of medicinal plants have a great potential for use in the culture of crustaceans as substitutes for chemical compounds against outbreaks of viral and bacterial diseases, as well as for use in food and as a breeding inducer. However, knowing that the responses depend to a large extent on the species and part of the plant to be evaluated, it is necessary to know the extraction solvent and the required dose through *in vitro* and *in vivo* test applications since it is essential to understand the mechanisms of metabolic and immunological action as well as molecular interaction of phytochemicals and crustacean to elucidate more clearly the responses and, therefore, their effectiveness.

Credit author contribution

R. Cortez-Mago: conceptualization, validation, writing-original draft, review and editing; L. Borges: review and editing; W. Wasielesky: conceptualization, validation, project administration, supervision, resources, funding acquisition, review and editing. All authors have read and accepted the published version of the manuscript.

Conflict of interest

The authors declare no potential conflict of interest in this manuscript.

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