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Review Article

Herbal Medicine Efficacy in Enhancing Crustacean Growth, Ovarian Maturation, and Immunity: A Review

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ABSTRACT

Crabs, lobsters, prawns, and shrimp are among the most highly prized crustaceans in the aquaculture industry and contribute significantly to the global economy. In crustacean farming, artificial chemotherapeutic drugs have been used to improve growth, ovarian maturation, and immunity. However, dependence on chemotherapeutics promotes antibiotic-resistant bacteria, pollutes the environment, and poses risks for human consumption. Therefore, the primary goal of this review article is to identify the various plants used to improve the growth, spawning, and immunity of crustaceans. The findings indicate that plants and herbs such as amaranth, soursop leaf, mulberry leaf, olive, cajuput, bitterweed, Shepherd's needle, Indian borage, Chinese skullcap, and Indian gooseberry can enhance crustacean growth. Herbs like common senduduk can promote ovarian maturation, resulting in 100% spawned crustaceans. Plants such as guava leaves, tall-stilt mangrove leaves, chaihu, Indian ginseng, rosemary, mangrove cannonball trees, lechuguilla, moringa, neem, screw pine, Indian gooseberry, solanum, buton forest onion, roselle, giant sensitive trees, and Tasmanian blue gum

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have been verified to have medicinal properties that can boost crustacean immunity. In conclusion, the knowledge gained from these findings may drive future research aimed at developing natural supplements or treatments to enhance growth, reproduction, and immune functions, ultimately benefiting crustacean farming.

Keywords: Crustacean, growth, immunity, ovarian maturation, plant extract

INTRODUCTION

Aquatic animals such as crustaceans are highly valued in the commercial market because of their delicious taste and rich in essential nutrients like vitamins, minerals, protein, amino acids, and fatty acids, which significantly contribute to their economic importance (Ahmadifar et al., 2021). Crabs, lobsters, prawns, and shrimp are among the highly prized crustaceans in the aquaculture industry and contribute significantly to the global economy (FAO, 2024). In 2022, global crustacean production surged to 12.7 million tonnes with penaeids shrimp stand out as the primary contributors to crustacean production, comprising 7.9 million tonnes, followed by crayfish (2.9 million tonnes) and crabs (1.2 million tonnes) (FAO, 2024). Main crustacean species being cultured in the world including white-leg shrimp (*Litopenaeus vannamei*), red swamp crayfish (*Procambarus clarkii*), Chinese mitten crab (*Eriocheir sinensis*), river prawn (*Penaeus monodon* and *Macrobrachium rosenbergii*) and swimming crabs (*Portunus* sp.) (FAO, 2024).

In crustacean farming, output or productivity could be increased by enhancing crustacean growth. Farmers tend to utilize synthetic hormones as the primary option to increase growth performance during crustacean farming. However, artificial hormone applications face challenges due to uncertain supply and rising prices, which undermines their usage (Hasnidar et al., 2021). The aquaculture industry has experienced consequences resulting from the use of synthetic hormones, which disrupt the health of surrounding aquatic animals and alter the sex ratio of affected species. This was evidenced by the spread of hormonal compounds through wastewater in aquaculture farming. Similarly, in modern times, the use of synthetic hormones in crustacean farming has resulted in significant consequences for humans, who consume these hormone-treated crustaceans, which affects human health. Since 2006, Europe has addressed such issues by implementing a ban on the use of drugs or chemicals in farmed animals (Lu et al., 2023a). Hence, plant products have been widely used in aquaculture to stimulate growth replacing drugs and chemical due to plants offer active compounds, such as alkaloids, terpenoids, saponins, and flavonoids (Ahmadifar et al., 2019). However, information regarding the use of plants on crustaceans needs to be gathered to reveal the mechanisms through which various plants affect crustacean growth.

In addition, seeds constitute one of the basic necessities or foundations of crustacean farming; hence, broodstock spawning is vital for initiating mass seed cultivation. To address the slow gonadal maturation of broodstock in aquaculture, eyestalk ablation is often introduced to suppress endogenous gonad-inhibiting hormone release by the eyestalk, which ultimately stimulates ovarian maturation in the broodstock (Farizah et al., 2017). However, several issues have arisen regarding ethics and the decreasing quality of eggs and larvae from broodstock with ablated eyestalks (Alam et al., 2017). The use of natural plants helps maintain crustacean welfare as an alternative to eyestalk ablation (Ahmadifar et al., 2019). Herbs and plant extracts are considered potential enhancers of ovarian maturation when applied to crustacean broodstock. For example, plant extracts contain numerous bioactive substances, such as vitamins and polyphenols, that may improve ovarian maturation in a variety of crustacean species (Dawood et al., 2017). Likewise, these herbs can promote the growth of beneficial microbial colonies in the digestive tract of broodstock, improving feed intake and providing the necessary nutrients for ovarian development (Moustafa et al., 2020). However, few studies have been conducted to explore the impact of these plants on improving ovarian maturation in crustaceans to date.

Disease outbreaks are frequent and significant challenges in the field of crustacean farming. Wu et al. (2021) indicated that *Vibrio* poses a difficulty in crab farming, resulting in an outbreak of milky disease. Similarly, other significant diseases that infect crabs include reovirus, dicisrovirus-1, bacterial pathogens and ciliate protozoans (Linh et al., 2017; Yue et al., 2023). Moreover, in shrimp farming, white spot syndrome is a disease that can affect the entire white-leg shrimp industry. In the prawn industry, nodavirus and extrasmall virus-like particles can cause white tail disease, which reduces the survival of larvae, postlarvae or juvenile prawns (Farook et al., 2016). Disease outbreaks in crustacean farming affect farming productivity to an extent, which has caused the aquaculture industry to collapse within a short period (Zhou et al., 2022). To overcome this issue, antibiotics are often used to control outbreaks (Wu et al., 2021). Antibiotics can be defined as substances that have the ability to kill or inhibit the growth of microorganisms while being safe for the host (Dawood et al., 2017). However, dependence on antibiotics in crustacean farming promotes antibiotic-resistant bacteria, leading to the emergence of drug-resistant strains (Ahmadifar et al., 2022), pollutes the environment and poses risks for human consumption (Yue et al., 2023). Thus, it is necessary to search for a non-chemotherapeutic method that serves a similar role as antibiotics, with the ability to kill microorganisms without affecting the crustacean as the host. Hence, the use of natural plants may improve crustacean health, as plants contain important phytochemical and plant secondary metabolites which act as antioxidants, antivirals, and antibacterials that activate specific immune system (Ahmadifar et al., 2021)

Given the beneficial effects of various plant on crustaceans and the great developments achieved through previous studies on crustaceans, the objective of present review is to identify all the plants that are potentially useful for commercial crustaceans, such as blue swimming crabs, mud crabs, crayfish, giant freshwater prawns, black tiger prawns and white-leg shrimp, and then to determine the ability of these specific plants to improve growth, ovarian maturation and immunity. This review also offers insight into the application of specific plant extracts in crustacean farming, including the conditions and techniques for introducing these specific plants to cultured crustaceans.

APPLICATION OF PLANT EXTRACTS IN CRUSTACEAN FARMING

Conditions for Choosing Plants

Several conditions should be taken into consideration before the commercialization of plants in the aquaculture industry. Certain conditions should be considered to ensure that the plants can be used for their medicinal properties for a prolonged period. The first condition is that plants should have antioxidant, antiviral, and antibacterial activities that promote growth, gonad maturation or immunity in crustaceans (Yue et al., 2023). These medicinal properties of plants are reflected by several active compounds inside them, such as phenols, polyphenols, alkaloids, quinones, triterpenoids, steroids, lectins, and polypeptides, all of which play a role in stimulating growth and immunity in crustaceans (Hasnidar et al., 2021). Plants have been verified to contain active compounds, such as phytoestrogens, which act as inducers of gonad maturation and antifertility, to stimulate the gonads of crustaceans. Phytoestrogens are vital active compounds that have a structure similar to that of oestradiol with a low molecular weight, allowing them to pass through cell membranes easily to bind with oestrogen receptors and stimulate an oestrogenic effect (Farizah et al., 2018). Determining the active compounds in plants could be achieved through compound screening via modern technologies, such as gas chromatography or conventional chromatography, before further experimentation with plants on crustaceans. To expedite this process, the use of plants that have previously been recognized as traditional local herbs (Table 1) with medicinal properties for humans could be effective for aquatic animals as well. For example, *Melastoma malabathricum L.*, known as a medicinal plant that promotes fertility and strengthens the human womb, has been proven effective in promoting ovary maturation in the mud crab *Scylla olivacea* (Farizah et al., 2018). Additionally, Chi et al. (2017) utilized herbs known to cure liver diseases in humans to treat hepatopancreas infection in aquaculture shrimp. Since the efficacy of plant supplementation is dose dependent, the optimal dose should be determined as the second condition. Administering plant concentrations below optimal doses does not affect crustacean growth or immunity, whereas too high a dose may sometimes act as an inhibitor of the immune response (Lu et al., 2023a). For example, Leite et al. (2021) reported that a too high rosemary concentration

Table 1
Previous herbs used in commercial aquaculture crustaceans

Commercialization of herbs	Crustacean species	Herbs	Reference
Commercialized as advanced product	Red claw crayfish, *Cherax quadricarinatus*	Coumarin extract from orchids and black beans (Sigma–Aldrich)	Zhou et al., 2022
	Giant freshwater prawn, *M. rosenbergii*	Polyherbal formulation (AquaImmu, Indian Herbs Supply and Research Company Limited) containing mixed herbs: • Basil, *Ocimum sanctum* • Indian ginseng, *Withania somnifera* • Heart-leaved moonseed, *Tinospora cordifolia* • Emblica, *Emblica officinalis*)	Kumari et al., 2004
	Black tiger shrimp, *P. monodon*	Polyherbal formulation (AquaImmu, Indian Herbs Supply and Research Company Limited) containing mixed herbs: • Basil, *O. sanctum* • Indian ginseng, *W. somnifera* • Heart-leaved moonseed, *T. cordifolia* • Emblica, *E. officinalis*	Chandran et al., 2016
	White-leg shrimp, *L. vannamei*	Polyherbal feed supplement (Ban-V trilobatum, Ideal Biosciences Private Limited) containing mixed herbs: • Turmeric, *Curcuma longa* • Guava, *Psidium guajava* • Holy basil, *O. sanctum* • Neem, *Azadirachta indica* • Birch-leaved cat tail, *Acalypha fruticose* • Indian pennywort, *Centella asiatica* • Waterhyssop, Bacopa *monnieri* • Sireh, *Piper betle* • Thumbai, *Leucas aspera*	Iyapparaj et al., 2021

Table 1 *(continue)*

Commercialization of herbs	Crustacean species	Herbs	Reference
		Polyherbal supplements (Phycurma Aquatic, Agrinusa Jaya Santosa company) containing mixed herbs: • Turmeric, *Cucurma domestica* • Javanese ginger, *Cucurma xanthorrhiza* • Gale of the wind, *Phyllantus niruri*	Putra et al., 2024
	Shrimp (NA species)	Cinnamon, *Cinnamomum cassia* (Ningbo Hangjing Biological Technology Co., LTD)	Zhang et al., 2023
Commercialized as traditional herbs, these are typically purchased from traditional medicine shops or commonly used in human food	Mud crab, *S. paramamosain*	Chinese gallnut, *G. chinensis*	Wu et al., 2021
	Red claw crayfish, *Cherax quadricarinatus*	Tochu, *Eucommia ulmoides* (leaf)	Lu et al., -2023a
	Giant freshwater prawn, *M. rosenbergii*	Peppermint, *Mentha piperita* (leaf)	Kawamura et al., 2019
		Lemongrass, *Cymbopogon citratus* (rhizome)	Adnan et al., 2021
		Rosemary, *Rosmarinus officinalis* (leaf)	Leite et al., 2021
	Black tiger shrimp, *P. monodon*	Ginger, *Boesenbergia pandurata* (rhizome)	Hardi et al., 2022
		Hairy-fruited eggplant, *Solanum ferox* (fruit)	Hardi et al., 2022
		Aloe vera (leaf)	Aftabuddin et al., 2017
		Green chiretta, *Andrographis pariculata* (leaf)	Aftabuddin et al., 2017
		Sugar apple, *Annona squamosa* (fruit)	Aftabuddin et al., 2017
		Neem, *A. indica* (leaf)	Aftabuddin et al., 2017
		Key lime, *Citrus aurantifolia* (leaf)	Aftabuddin et al., 2017
		Coriander, *Coriandrum sativum* (leaf)	Aftabuddin et al., 2017
		Holy basil, *Ocimum sanctum* (leaf)	Aftabuddin et al., 2017
		Onion, *Allium sepa*	Aftabuddin et al., 2017
		Guava, *P. guajava* (leaf)	Aftabuddin et al., 2017

Table 1 *(continue)*

Commercialization of herbs	Crustacean species	Herbs	Reference
	White-leg shrimp, *L. vannamei*	Dokudami, *Houttuynia cordata* (leaf)	Kawamura et al., 2019
		Peppermint, *M. piperita* (leaf)	Kawamura et al., 2019
		Red chilli, *C. annuum* (fruit)	Kawamura et al., 2019
		Ginger, *Zingiber officinale* (rhizome)	Kawamura et al., 2019
		Ginger, *Z. officinale* (rhizome)	Widowati et al., 2022
		Turmeric, *Cucurma domestica* (rhizome)	Widowati et al., 2022
		Temulawak, *Curcuma zanthorrhiza* (rhizome)	Widowati et al., 2022
		Green tea, *Camellia sinensis* (leaf)	Kongchuma et al., 2016
		Chinese skullcap, *Scutellaria baicalensis* (root)	Maurus et al., 2023
		Nightshades, *Solanum procumbens* (leaf)	Hong et al., 2022
		Cat's claw, *Uncaria tomentosa* (bark)	Junior, 2017
		Buton forest onion, *Eleutherine bulbosa* (bulb)	Munaeni et al., 2020
Collected from wild	Blue swimming crab, *Portunus pelagicus*	Common senduduk, *M. malabathricum* (leaf)	Alam et al., 2019
	Mud crab, *S. paramamosain*	Soursop, *A. muricata* (leaf)	Yue et al., 2023
	Mud crab, *S. olivacea*	Common senduduk, *M. malabathricum* (leaf)	Farizah et al., 2017
		Common senduduk, *M. malabathricum* (leaf)	Farizah et al., 2018
		Common senduduk, *M. malabathricum* (leaf)	Iromo et al., 2021
		Mulberry, *Morus alba* (leaf)	Fujaya et al., 2018
		Tall-stilt mangrove, *R. apiculata* (leaf)	Linh et al., 2017
	Red claw crayfish, *C. quadricarinatus*	Lempuyang, *Zingiber zerumbet* (flower)	Hardi et al., 2021
		Chaihu, *Radix bupleuri* (root)	Lu et al., 2023b
	Giant freshwater prawn, *M. rosenbergii*	Bermuda grass, *Cynodon dactylon* (leaf)	Farook et al., 2016

Table 1 *(continue)*

Commercialization of herbs	Crustacean species	Herbs	Reference
		Fiddlehead fern, *Diplazium esculentum* (leaf)	Hajar-Azira et al., 2023
		Indian ginseng, *W. somnifera* (root)	Harikrishnan et al., 2012
		Cajeput, *Melaleuca cajuputi* (leaf)	Sahimi et al., 2022
	Black tiger shrimp, *P. monodon*	Mangrove holly, *Acanthus ilicifolius* (leaf)	Saptiani et al., 2021
		Cannonball mangrove, *Xylocarpus granatum* (leaf)	Saptiani et al., 2020
	White-leg shrimp, *L. vannamei*	Buton forest onion, *E. bulbosa* (bulb)	Munaeni et al., 2019
		Papaya, *Carica papaya* (leaf)	Supono et al., 2019
		Ketapang, Terminalia catappa (leaf)	Supono et al., 2019
		Tall-stilt mangrove, R. apiculata (leaf)	Supono et al., 2019
		King of Bitters, *Andrographis paniculata* (leaf)	Yin et al., 2023
		Shepherd's Needles, *Bidens alba* (leaf)	Huang et al., 2022
		Mexican mint, *Plectranthus amboinicus* (leaf)	Huang et al., 2022
		Purple coneflower, *Echinacea purpurea* (root, leaf and flower)	Medina-Beltrán et al., 2012
		Cat's claw, *U. tomentosa* (bark)	Medina-Beltrán et al., 2012
		Indian ginseng, *W. somnifera* (root)	Abdel-Tawwab et al., 2022
		Moringa, *Moringa oleifera* (seeds and pods)	Lugo-Rubio et al., 2022
		Croton, *Croton californicus* (Petiole, leaves, and flowers)	Lugo-Rubio et al., 2022
		Moringa, *M. oleifera* (leaf)	Abidin et al., 2022
		Roselle, *Hibiscus sabdariffa* (fruit)	Nguyen et al., 2023
		Giant sensitive tree, *Mimosa pirga* (leaf)	Nguyen et al., 2023
		Tasmanian blue gum, *Eucalyptus globulus* (leaf)	Nguyen et al., 2023
Agricultural waste (byproduct)	Crayfish, *A. leptodactylus*	Olive, *Olea europaea* (wastewater of olive mill)	Parrillo et al., 2017
	White-leg shrimp, *L. vannamei*	Lechuguilla, *Agave lechuguilla* (bagasse)	Quiroz-Guzman et al., 2023
		Cacao, *Theobroma cacao* (Pod husk)	Chang et al., 2023

of 15% fed to the giant freshwater prawn *M. rosenbergii* promoted the production of reactive oxygen species that led to cell damage due to lipid peroxidation and decreased prawn growth. Similarly, Munaeni et al. (2020) reported lower intestinal microbe diversity through gel electrophoresis for fish given a higher dosage of rosemary extract at 25 g kg^{-1}, which slowed the immune response mechanism. The third condition is the availability of wild plants, which are freely accessible in vast quantities at no cost (Table 1). For example, Linh et al. (2017) utilized a mangrove plant leaf from *Rhizophora apiculata* to cure the megalopa of a mud crab, *S. paramamosain,* that was infected by ciliate protozoans. Sahimi et al. (2022) also utilized *Melaleuca cajuput* leaves as a feed additive to improve the growth of the giant freshwater prawn *M. rosenbergii.* Certainly, these tall-stilt mangrove and cajuput leaves are available at no cost and can be found in abundance, allowing farmers to use these plants without any constraints. A fourth condition is that plants and herbs could be obtained from industrial waste as part of an effort to eradicate waste from industries (Table 1). Parrillo et al. (2017) used wastewater from an olive processing mill to coat fish flesh before being fed crayfish, *Astacus leptodactylus*, resulting in improved moulting. Similarly, several previous studies have used leaves from commercial trees such as mulberry, guava, and roselle for enhancing growth and the immune system of mud crabs, *S. olivacea* (Fujaya et al., 2018) and *S. paramamosain* (Yue et al., 2023), and the white-leg shrimp, *Littopenaeus vannamei* (Nguyen et al., 2023), respectively. In conclusion, these third and fourth conditions, such as using wild plants or utilizing waste from the plantation industry, are imperative to reduce the costs of raw materials, making them viable for commercial use in crustacean farming. However, the efficacy of plants (first condition and second condition) in promoting the growth, spawning or immunity of crustaceans should be prioritized. Because a wide variety of herbs have been proven effective for use on commercial crustaceans, herbs could be further commercialized not only by involving a single herb but also by combining different herbs to increase their efficacy while offering various functions (Table 1).

Processing and Implementation of Plants

Previous studies often used leaf parts that were air dried, powdered and used directly for medicinal treatments. Additionally, the plant powder is further extracted by soaking (sometimes stirring) with a solvent such as ethanol (70–85%) or methanol with a ratio of 5- to 10-fold the solvent for 4 to 48 hours (Leite et al., 2021). Other solvents can be used to extract the plant by boiling it with distilled water or deionized water at 100 °C for 1 to 2 hours at a ratio of 5-fold solvent (Wu et al., 2021). The extract is then filtered through muslin cloth or Whatman paper no. 1 or centrifuged before being evaporated via a rotary evaporator at 40–50 °C and stored at 4–20 °C for further use (Hajar-Azira et al., 2023; Zhang et al., 2023). After plant extraction, four different techniques are applied to introduce the plants to cultured crustaceans: pelleting, coating, immersion, or injection. The most common technique used involves incorporating the plant powder in formulated pellets within a range of concentrations of 0.5–2 g/kg. For ready-made pellets, coating techniques can be used to encapsulate feeds with plant extracts via two different coatings. This dual-layer coating process prevents any leaching of the plant extract into the surrounding water. The feed can be initially coated with a plant extract as the first layer, followed by a second layer coating with either chitosan (1% or 3%) (Ali et al., 2023; Fujaya et al., 2018) or squid oil (2%) (Nguyen et al., 2023). The chitosan solution is prepared by using acetic acid as a solvent (Fujaya et al., 2018). After the first layer of coating, the pellet was dried at room temperature for 30 minutes before the second layer was applied and then dried at room temperature for 5 hours (Medina-Beltrán et al., 2012). Additionally, instead of pellets, raw materials such as fish can be coated by soaking them with plant extracts for 20 to 30 minutes, air dried and layered with a chitosan solution or squid oil (Ali et al., 2023). The dosage of plant extract typically ranges from 0.8 to 10 g of plant extract per kilogram of feed (Lu et al., 2023b; Nguyen et al., 2023). For the immersion technique, medicinal treatment is achieved by dissolving the plant powder within the range of 1000 to 6000 mg per litre of seawater (Anirudhan et al., 2021; Linh et al., 2017), with the main purpose of using this technique to cure cultured crustaceans from any disease or parasite infection. Another technique is injection, which is specialized for stimulating the gonads and spawning of broodstock. Given that this technique demands skilled labour and is applicable only to a restricted number of broodstock, it has been used primarily for crabs, as a single mother crab can yield over a million eggs. Previously, several doses of plant extract were applied, ranging from 20 µg to 1 mg of plant extract per gram of crab body weight (Alam et al., 2019; Farizah et al., 2018). Overall, four techniques can be applied for plant or herb administration in crustacean farming, either through pellets, coatings, immersion, or injection; all these techniques should be in accordance with the purpose of plant use.

ROLE OF PLANT ADDITIVES ON CRUSTACEAN GROWTH AND FEEDING

Herbs or medicinal plants contain compounds that can enhance growth performance in terms of survival, growth, and moulting. To improve the growth of crabs, several herbs, such as amaranth (*Amaranthus* sp.), soursop leaf (*A. muricata*), and mulberry leaf (*M. alba*), have been identified and shown to increase growth. For crayfish (*A. leptodactylus*) and giant freshwater prawn (*Macrobrachium rosenbergii*), plants such as cajaput (*M. cajuputi*), olive (*O. europaea*) and fiddlehead fern (*D. esculentum*) have been verified to positively affect their growth. Moreover, for white-leg shrimp, several plants are able to improve shrimp growth, such as bitterweed (*Andrographis paniculate*) shepherd's needles (*B. alba*), Indian borage (*P. amboinicus*)*, Mexican mint (P. amboinicus),* Chinese skullcap (*S. baicalensis),* and Indian gooseberry (*Phyllanthus amarus*), as well as commercial products such as Ban-V. Interestingly, plants that can benefit the survival of crustaceans, such as mud crab (*S. olivacea*), crayfish (*A. leptodactylus*), and white-leg shrimp (*L. vannamei*) given plant additives such as soursop leaf (*A. muricata*), olive (*O. europaea*) and the king of bitters (*A. paniculata*), reach survival rates of more than 80%, 81.5%, and 93.3%, respectively (Ali et al., 2023; Parrillo et al., 2017; Yin et al., 2023). In addition to survival, crustaceans fed plant additives are more likely to show significant growth in terms of weight gain and specific growth rate. Table 2 shows that crustaceans such as mud crab (*S. olivacea*) had a greater growth rate percentage after being provided with soursop leaf (*A. muricata*) (16.5%) than after being provided the control diet (15.8%). Other studies by Parrillo et al. (2017) revealed a greater specific growth rate (SGR) for crayfish (*A. leptodactylus*) supplemented with 15 g/kg olive (*O. ueropaea*) additive (SGR: 0.32% day^{-1}) than for the control (SGR: 0.21% day^{-1}). Similarly, a study by Sahimi et al. (2022) and Hajar-Azira et al. (2023) reported a weight increase of approximately 2-fold for giant freshwater prawns (*M. rosenbergii*) fed with cajuput (*M. cajuputi*) and fiddlehead fern (*Diplazium esculentum*) with weight gains of 1.1 g and 50 mg, respectively, compared with the control treatment (weight gains of 0.5 g and 20 mg, respectively). For white-leg shrimp, several listed plant additives, such as bitterweed (*A. paniculata*), shepherd's needle (*B. alba*), Indian borage (*P. amboinicus*), Chinese skullcap (*S. baicalensis*) and Indian gooseberry (*P. amarus*), have been verified to increase their growth (Table 2). Interestingly, the use of plant additives such as Shepherd's needle (*B. alba*) (SGR: 16% day^{-1}) and Indian borage (*P. amboinicus*) (SGR: 17% day^{-1}) increased the SGR approximately 2-fold compared with that of the control group (SGR: 9.34% day^{-1}) (Huang et al., 2022).

Plant extracts aid in promoting crustacean growth through a vital compound known as phytoecdysteroid, which is found in the leaves of plants (Hajar-Azira et al., 2023). Phytoecdysteroids have a four-ring skeleton composed of 27, 28, 29, or 30 carbon atoms (derived from plant sterols), and the most common phytoecdysteroid is 20-hydroxyecdysone (Arif et al., 2022). In crustaceans, 20-hydroxyecdysone is known as a moulting hormone, which is imperative for promoting ecdysis in crustaceans (Fujaya et al., 2018). Instead of depending on the Y-organ for the secretion of the moulting hormone, providing plant leaves that contain high levels of phytoecdysteroids leads to ecdysteroid elevation in the crustacean haemolymph and acts as a signal for triggering moulting occurrence in crustaceans (Hasnidar et al., 2021). The moulting process is required for the crustacean to shed the old carapace and grow in size, and the moulting process ends with the formation of a new carapace that slowly hardens. In addition, plant extracts improve crustacean growth performance by optimizing feed absorption through a healthy digestive tract (Quiroz-Guzman et al., 2023). Through qPCR, the incorporation of plant extracts in the crustacean diet caused the upregulation of the expression of several genes related to amylase, protease, and lipase in the hepatopancreas, stomach, and intestine, leading to the secretion of more digestive enzymes (Yin et al., 2023). The increase in digestive enzyme activity promotes the catabolism of glycogen, protein, and lipids for better absorption and, subsequently, increases the feed conversion ratio of crustaceans (Abdel-Tawwab et al., 2022; Lu et al., 2023b). Additionally, the presence of plant extracts in crustacean feed positively influences the morphology of the hepatopancreas and intestines to improve the absorptive ability of various nutrients (Lu et al., 2023a). Crustaceans fed with plant extracts presented increased numbers of intestinal goblet cells, intestinal villus heights, widths of the intestinal lamina propria, and mucosal folds; all of these morphological enhancements increase the surface area available for efficient nutrient absorption, thus promoting crustacean growth (Abdel-Tawwab et al., 2022). One of the active compounds, especially polyphenols in plant extracts, stimulates digestion activity, which increases crustacean appetite (Hajar-Azira et al., 2023; Yue et al., 2023;). Since these phenolic compounds have antimicrobial characteristics, they may have bactericidal effects on the gut microflora. The microbial properties of the plant extract shift the microbial ecology in the crustacean gut by preventing pathogen colonization and providing a diverse gut ecosystem (Sahimi et al., 2022). This increase in bacterial diversity leads to a greater level of intra- and interspecific competition, thereby reducing the niches available for the colonization of pathogenic microorganisms (Quiroz-Guzman et al., 2023). This phenomenon has also been observed in pathogen-infected crustaceans, where plant additives shift the dominance of *Vibrio* in the crustacean gut and intestine to a greater abundance of *Bacilli* and cyanobacteria (Quiroz-Guzman et al., 2023). Plant incorporation into the crustacean diet not only reduces pathogen infection in the digestive system but also serves oligosaccharides as a feed source for the microbial community, enhancing crustacean digestion and leading to increased growth performance (Quiroz-Guzman et al., 2023).

ROLE OF PLANT ADDITIVES ON CRUSTACEAN REPRODUCTION

Current research on crustacean reproduction has focused only on crab species, such as the blue swimming crab (*P. pelagicus*) and mud crabs from two species, *S. serrata* and *S. olivacea (Table 3)*. All three studies used common senduduk with an injection technique to substantially improve the ovarian maturation of crabs, and these experiments were verified through several analyses, including hormone levels (i.e., oestradiol), gonad volume (i.e., gonadosmatic index (GSI) and oocyte size) and the spawning rate. Farizah et al. (2018) reported that the oestradiol level in the haemolymph of the mud crab *S. olivacea,* injected with 1.00 mg/g (oestradiol: 48.6 pg/ml) of common senduduk, was more than double that of the mud crab in the control group (oestradiol: 25.5 pg/ml). This, in turn, induced oocyte growth in the mud crab ovary, as evidenced by the greater oocyte diameter (113 μm) and GSI (14.1). Similarly, another study by Iromo et al. (2021) demonstrated an increase in the

Table 2
Effects of plant extracts on the growth performance and feeding of crustaceans

Crustacean species	Plant extract	Optimal dose	Growth indicators				Reference
			Survival	WG	SGR	Moulting	
Mud crab, *S. olivacea*	Amaranth, *Amaranthus sp.*	42 µg/ml*	●			●	Hasnidar et al., 2021
	Soursop, *A. muricata* (leaf)	0.6 g/kg	●			●	Ali et al., 2023
	Mulberry, *M. alba* (leaf)	2.7 g/kg				●	Fujaya et al., 2018
Crayfish, *A. leptodactylus*	Olive, *O. europaea* (wastewater of olive mill)	5.0 g/kg	●		●		Parrillo et al., 2017
Giant freshwater prawn, *M. rosenbergii*	Fiddlehead fern, *D. esculentum* (leaf)	10 g/kg	●	●			Hajar-Azira et al., 2023
	Cajeput, *M. cajuputi* (leaf)	15 g/kg		●			Sahimi et al., 2022
Black tiger shrimp, *P. monodon*	AquaImmu product (mixed herbs, refer Table 1)	300 g/kg			●		Chandran et al., 2016
	Mix of ginger, *B. pandurata* (rhizome) and hairy-fruited eggplant, *S. ferox* (fruit) with ratio 2:1	30 g/kg	●		●		Hardi et al., 2022
White-leg shrimp, *L. vannamei*	King of Bitters, *A. paniculata* (leaf)	5 g/kg	●	●			Yin et al., 2023
	Shepherd's Needles, *B. alba* (leaf)	20 g/kg			●		Huang et al., 2022
	Mexican mint, *P. amboinicus* (leaf)	20 g/kg			●		Huang et al., 2022
	Chinese skullcap, *S. baicalensis* (root)	10 g/kg		●			Maurus et al., 2023)
	Indian gooseberry, *P. amarus* (leaf)	20 g/kg	●	●			Ngo et al., 2020
	Ban-V product (mixed herbs, refer Table 1)	20 g/kg	●		●		Iyaparaj et al., 2020
	Buton forest onion, *E. bulbosa* (bulb)	40 g/kg		●			Munaeni et al., 2019
	Mixed herbs consisting ginger, *Z. officinale* (rhizome), turmeric, *Cucurma domestica* (rhizome), temulawak, *Curcuma zanthorrhiza* (rhizome)	NA		●			Widowati et al., 2022

Note: SGR: Specific growth rate. Many of the crustaceans were given plant extract through feeding, while those given plant extract via injection are indicated by the symbol *. The green circle indicates results of growth performance that are better than the control treatment (without the plant extract) gonadosomatic index (GSI) for the mud crab *S. serrata* injected with 0.01 mg/g of common senduduk (GSI: 18.1) compared with that of crabs without common senduduk injection (GSI: 15.2). The use of common senduduk not only ensures that the ovarian stimulation of crabs occurs at the highest rate but also aids in increasing the number of spawned crabs. This occurrence was reported by Alam et al. (2019), who reported that all blue swimming crabs, *P. pelagicus,* injected with common senduduk at concentrations of 15 and 20 µg/g were completely spawned (100%), whereas those crabs given 5 and 10 µg/g had spawning rates of 67 and 67%, respectively. In contrast, the control groups presented the lowest spawning rate, at only 33%. To date, only one herb has been used to promote the ovarian growth of crabs. More studies are needed to collect information from other potential herbs or plants that could enhance the ovarian maturation of crustaceans or perhaps expand the use of common senduduk on other crustacean groups to obtain more data on this herb's efficacy for increasing spawning, either in lobsters, prawns, or shrimp.

Table 3
Effects of plant extracts on the reproductive performance of crustaceans

Crustacean species	Plant extract	Optimal dose	Reproductive indicators				Reference
			Spawning rate	GSI	Oocyte size	Oestradiol	
Blue swimming crab, *P. pelagicus*	Common senduduk, *M. malabathricum*	15-20 µg/g	●				Alam et al., 2019
Mud crab, *S. serrata*	Common senduduk, *M. malabathricum*	0.01 mg/g		●			Iromo et al., 2021
Mud crab, *S. olivacea*	Common senduduk, *M. malabathricum*	1.00 mg/g		●	●	●	Farizah et al., 2018

Note: GSI: The green circle indicates result of reproductive indicators better than control treatment (without given plant extract). All the crabs here were given plant extract via injection

Plant extracts contain bioactive compounds, especially phytoestrogens, that have a similar structure to oestradiol, resulting in effects similar to those of steroid hormones in stimulating reproduction in crustaceans (Iromo et al., 2021). Since these phytoestrogens have a low molecular weight, they easily move in crustacean haemolymph, pass through cell membranes and bind with oestrogen receptors to induce Vtg expression in the ovary oocyte (Farizah et al., 2017) and hepatopancreas (Iromo et al., 2021). This expression then stimulates vitellin deposition and the proliferation of yolk globules in crustacean ovaries, leading to ovary volume enlargement and colour changes from white to deep orange (Farizah et al., 2018). In addition, hormones such as ecdysteroid, known for regulating moulting in crustaceans, are known to promote reproduction (Sumiya et al., 2014). The expression of ecdysone commonly commences in the Y-organ and becomes 20-hydroxyecdysone (20E), the biologically active form of ecdysteroid that promotes vitellogenesis for ovarian growth (Gong et al., 2015). Although without endogenous 20-hydroxyecdysone, the incorporation of plant extract (containing phytoecdysteroids) in crustacean feed causes an increase in this hormone in crustacean haemolymph. In plants, phytoecdysteroids play a role in enhancing plant immunity against predators, particularly during the reproductive stage, when their concentration is highest, and these compounds accumulate in reproductive organs such as seeds and roots (Arif et al., 2022). Since phytoecdysteroids are polyhydroxylated steroids with a structure resembling that of the crustacean-moulting hormone, such steroids are able to improve gonad maturation in crustaceans when included in their diet (Dinan et al., 2021). These phytoecdysteroids are sent via haemolymph into ovarian tissue and bind with EcR (ecdysone receptor), activating the ecdysteroid signalling pathway (Gong et al., 2015). After binding with phytoecdysteroid, EcR forms a heterodimer that interacts with the 50-promoter region of the Vg gene, promoting its transcription (Gong et al., 2015). This leads to the synthesis of vitellogenin in the ovary, resulting in yolk accumulation, and the ovary undergoes gradual changes, transitioning from white to an orange–reddish colour (Farizah et al., 2018). Other bioactive compounds from plant extracts that play important roles in ovarian development include α-tocopherol. Since α-tocopherol (known as vitamin E) is lipid soluble, it easily accumulates in the ovary oocyte and acts as a natural antioxidant (Li et al., 2018). In the oocyte, α-tocopherol protects membranes and organelles from oxidation by scavenging organic free radicals (Wouters et al., 2001) and prevents peroxides resulting from lipid metabolism (Lebold & Traber. 2014). This biological role of α-tocopherol subsequently aids in ovarian maturation, fertilization, and egg hatchability in crustacean female broodstock (Li et al., 2018). The role of α-tocopherol does not cease during the postspawning event, as a previous study reported a high level of α-tocopherol in crustacean larvae, providing evidence for the importance of α-tocopherol in larval development as well (Wouters et al., 2001).

ROLE OF PLANT ADDITIVES ON CRUSTACEAN IMMUNITY

Increasing prices, along with the increasing demand for crustaceans, have led to the mass culture of crustacean species. Unfortunately, currently, the greatest challenge in crustacean farming is maintaining the health of commercial crustaceans in the aquaculture industry. Many studies have focused on commercial crustacean species such as the mud crab (*S. paramamosain*), red claw crayfish (*C. quadrinatus*), giant freshwater prawn (*M. rosenbergii*), and black tiger shrimp (*P. monodon*). White-leg shrimp is the most attractive species for use as experimental specimens because this aquatic animal is the most crustacean farmed, and disease outbreaks have halted aquaculture operations to the extent that entire farms have collapsed, resulting in millions of losses. To ensure the efficacy of the plants, a challenge test was conducted, and the crustacean specimens were exposed to several harmful pathogens, such as *Vibrio harveyi, V. parahaemolyticus, V. alginolyticus, Aeromonas hydrophilia* and microcystin-LR (Table 4). Previous evidence verified that several medicinal plants, such as mangrove cannonball trees, lechuguilla deserts, neems, screw pines, Indian gooseberries, solanum, buton forest onion, giant sensitive trees, and tall-stilt mangroves, were able to cure *Vibrio* sp. infection. Moreover, medicinal plants such as tochu and chaihu are able to resist microcystin-LR, and herbs such as Indian ginseng can cure diseases caused by *A. hydrophila*. Interestingly, despite white-leg shrimp being infected with *Vibrio*, the survival of shrimps fed lechuguillas (Quiroz-Guzmán et al., 2023), neems (Morales-Covarrubias et al., 2016) and Indian gooseberries (Ngo et al., 2020) was 100, 75.8 and 72.6%, respectively, greater than that of shrimp in the control treatment (>50%). In addition to conducting challenge tests, plant efficacy was tested via immunity-related analyses, such as alkaline phosphatase (AKP), catalase (CAT), glutathione peroxidase (GPx), glutathione S transferase (GST), malondialdehyde (MDA), phenoloxidase (PO), reduced glutathione (GSH), superoxide dismutase (SOD) and total antioxidant capacity (T-AOC) analyses. Some of these components are part of the body's antioxidant defence system, working together to neutralize reactive oxygen species and minimize oxidative damage to cells and tissues in crustaceans. For crabs, Yue et al. (2023) reported that an increase in SOD and GST simultaneously reduced the MDA content after the mud crab, and *S. paramamosain* fed leaf guava as a feeding additive at a concentration of 230 mg/kg. For lobster, Lu et al. (2023a, 2023b) reported that red claw crayfish *C. quadrinatus* provided with tochu and chaihu at concentrations of 1.0 and 0.8 g/kg, respectively, presented relatively higher AKP, CAT, GPx, GSH, GST, PO, SOD, and T-AOC and, at the same time, reduced MDA levels (Table 4). For prawn species, giant freshwater prawns (*M. rosenbergii*) presented increased PO (absorbance: 3.09) and SOD (4.66 U/mg prot^{-1}) levels in response to Indian ginseng fed a concentration of 1.0% (Harikrishnan et al., 2012). Moreover, giant freshwater prawns fed with rosemary at a concentration of 5% presented relatively high GSH, GR and GST contents, with values of 80 mmol mL^{-1}, 501 nmol mL^{-1}, and 0.41 mmol min^{-1} mg prot^{-1}, respectively (Leite et al., 2021). For shrimp, the incorporation of plant additives such as Indian ginseng at a concentration of 2.0 g/kg into white-leg shrimp (*L. vannamei*) builds a better immune system by increasing the levels of CAT, GPx, GSH, and T-AOC and reducing the levels of MDA (Table 4).

To date, only one study has addressed the larval stage of crustaceans, referring to a study by Linh et al. (2017), which used tall-stilt mangrove leaves, *R. apiculata, t*o alleviate ciliate and protozoan infection during the Megalopal stage of the mud crab. It is imperative to carry out experiments related to crustacean larvae since this phase is considered a fragile stage due to the incomplete development of the immune system, which increases susceptibility to disease and pathogen infection. The crustacean larval phase is often vulnerable to *Vibrio* infection, which decreases larval survival in a hatchery within a short period. Therefore, to make substantial improvements in crustacean larval farming, plants and herbs such as mangrove cannonball trees, lechuguilla, Indian ginseng, neem, screw pine, Indian gooseberry, and *Solomon procumbens*, as well as forest onions, and giant sensitive trees should have their applications expanded to crustacean larvae to ensure larval resilience against *Vibrio* infection. Established products such as AquaImmu, Ban-V, and Phycurma aquatic could also be used for larval rearing because of their ability to promote bactericidal, antioxidant and lysozyme activities. The two best possible techniques that could be implemented for larval farming are immersion, by dissolving plant powder in the larval tank, or enrichment, by enriching the artemia with medicinal plants before feeding the artemia to crustacean larvae. The effect of the disease is minimized with high-yield larval output, which could be improved in crustacean farming. Additionally, this is one of the initiatives to curb antibiotic usage, especially in crustacean species with very low larval survival, such as mud crabs, blue swimming crabs, and spiny lobsters.

Phenolic compounds such as polyphenols, flavonoids, and tannins (see Table 5) are some of the natural compounds derived from plants that have potent antimicrobial activity against several strains of bacteria (Parrillo et al., 2017). Phenolic compounds inactivate microbial adhesions that are vital for facilitating the attachment of microorganisms to host tissues or cells. Additionally, the phenolic–lipophilic characteristics cause the cytoplasmic membrane of bacteria to dissolve, leading to the leakage of intracellular constituents, killing the bacteria (Sahimi et al., 2022). In addition to damaging the bacterial cell membrane, phenolic compounds offer bacteriolytic properties, including preventing the cell division of bacteria and reducing their biofilm-forming ability (Quiroz-Guzman et al., 2023). Phenolic compounds also act as prebiotic agents for the growth of the gut microbiota. Polyphenols increase the number of good bacteria while simultaneously inhibiting the proliferation of pathogenic bacteria in the intestinal tract (Lu et al., 2023b). Good bacteria, such as *Lactobacillus*, can metabolize polyphenol compounds to generate energy. Some phenolic compounds, such as flavonoids, tannins, and saponins, can reduce cholesterol levels since these phenolic compounds compete with cholesterol for the same receptors, preventing its absorption in the crustacean digestive tract and reducing blood cholesterol levels (Ali et al., 2023). The accumulation of cholesterol increases oxidative stress and may block blood flow, thus decreasing the oxygen supply to target cells. Since phenolic compounds can stimulate the secretion of bile salts, which are crucial for emulsifying fats in the intestine, these findings indicate that phenolic compounds indirectly contribute to the elimination of LDL cholesterol via the digestion process (Ali et al., 2023). Additionally, plant additives

Table 4
Effects of plant extracts on the immunity of crustaceans

Crustacean	Plant extract	Opt dose	Antioxidant indicators							Other immunity indicators					Challenge test				Reference
			CAT	GSH	GPx	GST	SOD	T-AOC	MDA	PO	AKP	Haemocyte count	Lysozyme	Phagocytic activity	*Aeromonas*	Microcystin-LR	Protozoan	*Vibrio*	
Mud crab, *S. paramamosain*	Guava, *P. guajava* (L)	0.3 g/kg				●	●		●										Yue et al., 2023
	Tall-stilt mangrove, *R. apiculata* (L)	1.0 g/l*															●		Linh et al., 2017
Red claw crayfish, *C. quadrinatus*	Tochu, *E. ulmoides* (L)	1.0 g/kg	●	●	●	●	●	●		●	●					●			Lu et al., 2023a
	Chaihu, *R. bupleuri* (R)	0.8 g/kg	●		●	●	●	●	●	●	●					●			Lu et al., 2023b
Giant freshwater prawn, *M. rosenbergii*	Indian ginseng, *W. somnifera* (R)	1 g/kg					●			●					●				Harikrishnan et al., 2016
	Rosemary, *R. officinalis* (L)	5 g/kg		●		●													Leite et al., 2021
	Cannonball mangrove, *X. granatum* (L)	1.25 g/kg												●				●	Saptiani et al., 2020
	AquaImmu product (Table 1)	1 g/kg								●			●						Sahoo et al., 2004
	Ban-V product (Table 1)	20 g/kg					●			●		●	●						Iyaparaj et al., 2020
Black tiger shrimp, *P. monodon*	AquaImmu product (Table 1)	300 g/kg								●		●							Chandran et al., 2016
	Mixed of nine herbs, (Table 1)	2.5 ml/kg	●	●	●		●							●				●	Aftabuddin et al., 2017
White-leg shrimp *L. vanname*	Indian ginseng, *W. somnifera* (R)	1.0 g/kg																●	Abdel-Tawwab et al., 2022
	Neem, *A. indica* (L)	0.5 g/kg																●	Morales-Covarrubias et al., 2016
	Lechuguilla, *A. lechuguilla* (L)	1-3 g/kg																●	Quiroz-Guzman et al., 2023

Table 4 *(continue)*

Crustacean	Plant extract	Opt dose	Antioxidant indicators							Other immunity indicators					Challenge test				Reference
			CAT	GSH	GPx	GST	SOD	T-AOC	MDA	PO	AKP	Haemocyte count	Lysozyme	Phagocytic activity	*Aeromonas*	Microcystin-LR	Protozoan	*Vibrio*	
	Buton forest onion, *E. bulbosa* (B)	12.5 g/kg								●		●						●	Munaeni et al., 2020
	Nightshades, *S. procumbens* (L)	15 g/kg										●						●	Hong et al., 2022
	Screw pine, *P. tectorius* (F)	6 g/l*																●	Anirudhan et al., 2021
	Indian gooseberry, *P. amarus* (L)	40 g/kg								●		●		●				●	Ngo et al., 2020
	Roselle, *H. sabdariffa* (fruit), Giant sensitive tree, *M. pirga* (L), Tasmanian blue gum, *E. globulus* (leaf)	10 g/kg																●	Nguyen et al., 2023
	Phycurma aquatic product (Table 1)	5 ml/kg					●		●									●	Putra et al., 2024
	Papaya, *Carica papaya* (L), Ketapang, *Terminalia catappa* (L), and tall-stilt mangrove, *R. apiculata* (L)	0.7 g/l*																●	Supono et al., 2019

Note: B: bulb, F: fruit, L: leaf, R: root, AKP: alkaline phosphatase, CAT: catalase, GSH: reduced glutathione, GPx: glutathione peroxidase, GR: glutathione reductase, GST: glutathione S transferase, MDA: malondialdehyde, PO: phenoloxidase, SOD: superoxide dismutase, T-AOC: total antioxidant capacity. Many of the crustaceans were given plant extract through feeding, while those given plant extract via immersion are indicated by the symbol *. The green circle indicates immune indicator results that are better than those of the control treatment (without the plant extract), while the blue circle indicates the ability to cure the infection.

Table 5
Imperative compounds that could enhance the immunity and growth of crustaceans

Crustacean species	Plant extract	Bioactive compounds								Challenge test									Reference
		Alkaloids	Coumarin	Flavonoids	Phenols	Saponins	Steroids	Tannins	Terpenoids	Ciliate protozoans	Microcystein-LR	*Pseudomonas*	*Vibrio*	*Acinobacter*	*Aeromonas*	*Stenotrophomonas*	*Morganella*	WSS virus	
Mud crab, *S. paramamosain*	Tall-stilt mangrove, *R. apiculata*			●	●	●		●	●	●									Linh et al., 2017
Lobster, *C. quadrinatus*	Tochu leaf, *E. ulmoides*					●					●								Lu et al., 2023a
Giant freshwater prawn, *M. rosenbergii*	Fiddlehead fern, *D. esculentum*			●	●	●	●	●	●										Hajar-Azira et al., 2023
	Soapbush, *Clidemia Hirta*			●		●			●			●	●	●	●	●	●		Musa et al., 2011
Black tiger shrimp,*P. monodon*	Mangrove cannonball leaf, *X. granatum*	●		●	●			●					●						Saptiani et al., 2020
White-leg shrimp, *Litopenaeus vannamei*	Lechuguilla, *A. Lechuguilla*			●									●						Quiroz-Guzman et al., 2023
	Cat's claw, *Uncaria tomentosa*	●	●	●	●			●	●									●	Junior et al., 2017

Note: Phytochemical screening of compounds in previous studies was conducted thoroughly via advanced chromatography techniques such as high-performance liquid chromatography (HPLC) and gas chromatography–mass spectrometry (GC–MS) or via conventional chromatography techniques such as thin-layer chromatography. The green circle indicates the presence of bioactive compounds in the plant, while the blue circle indicates that the plant is able to cure infection can induce the expression of antimicrobial peptides involved in strengthening the innate immunity of crustaceans, such as penaeidin (Pen2, Pen3, Pen4), anti-lipopolysaccharide factor (ALF), anti-crustin protein (ACP Crus), and lysozyme (Lyz), with these peptides participating in antimicrobial activities through several mechanisms. For example, penaeidin, also known as an antimicrobial peptide with chitin-binding activity, is secreted in haemolymph granulocytes to eliminate microorganisms that are engulfed by granulocytes (Anirudhan et al., 2021). Other peptides, such as ACP, are involved in enhancing the recognition and phagocytosis of foreign bodies (Yue et al., 2023), whereas Lyz peptides are involved in cleaving β-1,4 glycosidic bonds between N-acetylmuramic acid and N-acetylglucosamine, which causes lysis of the bacterial cell wall (Abidin et al., 2022).

The bioactive compounds in plant extracts improve antioxidant enzyme activities to withstand reactive oxygen species (ROS) that are harmful to host cells. ROS-induced damage in crustaceans is neutralized via enzymatic antioxidant defence mechanisms such as catalase (CAT), glutathione peroxidase (GPx), glutathione reductase (GR), glutathione S-transferase (GST), phenoloxidase (PO), reduced glutathione (GSH), and superoxide dismutase (SOD). Many researchers have reported that these antioxidant enzymes increase in crustacean haemolymph, ovaries, or hepatopancreas after supplementation with plant extracts. Lu et al., (2023b) reported an increase in the mRNA expression levels of antioxidant enzymes such as CAT, SOD (cMN-SOD), GST, and GPx (GPx, GPx3P, Se-GPx), which are involved in key pathways to eliminate unnecessary free superoxide anion radicals in crustaceans. The SOD enzyme converts superoxide radicals (O2) into hydrogen peroxide (H2O2), which is then detoxified by CAT and GPx enzymes (Harikrishnan et al., 2012; Li et al., 2021). Other antioxidant enzymes, such as GST, play a role in converting xenobiotics (foreign compounds) to xenobiotic-GSH conjugates that are less toxic and more easily excreted (Cheng et al., 2020), whereas GR enzymes function to catalyse the conversion of oxidized glutathione into reduced glutathione (GSH), allowing the antioxidant function of GSH to continue. GSH donates electrons to neutralize ROS, preventing oxidative stress in crustacean tissues. In addition to these mechanisms, phenolic compounds in plants upregulate proPO and ProPO2 expression, thereby activating the PO enzyme for melanization (a process in which phenol interacts with quinone, which is then polymerized to form melanin) in the haemolymph or hepatopancreas, which encapsulates and immobilizes any pathogen (Anirudhan et al., 2021; Munaeni et al., 2020; Scherping & Watson, 2021).

ROLE OF PLANT ADDITIVES AGAINST ENVIRONMENTAL STRESS

With ongoing climate change worldwide, alterations in temperature, salinity, and pH are increasingly exceeding the tolerance limits of crustaceans. Even slight temperature changes can have detrimental effects on the physiological balance of crustaceans, potentially leading to mortality. In shrimp aquaculture, temperature fluctuations are common, and it has been documented that white-leg shrimp (*Litopenaeus vannamei*) stop feeding when exposed to unfavorable temperatures. Both excessively high and low temperatures can induce oxidative stress, overwhelm antioxidant defense mechanisms, and suppress immune function (Zabolinia et al., 2024). Salinity stress can increase gill Na^+/K^+-ATPase activity, cause swelling in gill filaments and in response to this severe condition, the transcription levels of 272 genes related to ion transport, energy metabolism, osmolyte metabolism, and methyltransferase activity are upregulated to enhance the osmoregulatory capacity of crustaceans (Xu et al., 2023). Similarly, pH fluctuations may disrupt the ionic balance in the gills, leading to decreased metabolic activity (Castro, 2022). Due to these vulnerabilities, there is growing interest in incorporating medicinal plants and herbs to enhance crustacean resilience against environmental stress. Several studies have evaluated the use of plants such as Indian ginseng (*Withania somnifera*), ginger (*Zingiber officinale*), red seaweed (*Gracilaria tenuistipitata* and *Kappaphycus alvarezii*), mesquite (*Prosopis juliflora*), green seaweed (*Ulva ohnoi*), noni fruit (*Morinda citrifolia*) and Moringa (*Moringa oleifera*) through dietary supplementation or immersion to improve stress resistance in crustaceans, particularly in white-leg shrimp (see Table 6). Overall, previous studies have shown that crustaceans, particularly white-leg shrimp, fed with plant extracts exhibit higher tolerance and increased survival under salinity, temperature or ammonia stress.

Upon exposure to environmental stressors, compounds in the plant including phenol, flavonoid and carotenoid activate a suite of protective responses, involving heat shock protein 70 (Hsp70). Hsp70 is stress protein belongs to a family of highly conserved stress proteins (~70 kDa) that are critical for protein biogenesis and homeostasis, and their functions include maintaining protein structure, repairing damaged cytoskeletal elements, and assisting in protein folding and hormone receptor function (Castro, 2022). For example, *Artemia* treated with Indian ginseng, *W. somnifera* showed a 3.5-fold upregulation of Hsp70 expression compared to the control group after exposure to stressors such as temperature, pH, and salinity (Castro, 2022). Hsp70 further initiates the activation of various defense mechanisms, including superoxide dismutase (SOD), glutathione peroxidase (GPx), phenoloxidase (PO), and lysozyme, which are essential for neutralizing harmful reactive oxygen species in crustaceans (Yeh et al., 2010; Zabolinia et al., 2024). Overall, the compounds in the plant play an essential role in scavenging reactive oxygen species and reducing oxidative damage, allowing lipids, proteins, and DNA to carry out their functions even when the crustacean exposed to environmental stress (Romadhoni et al., 2020).

GAP STUDY, CONCLUSION, AND FUTURE PERSPECTIVE

In aquaculture, two crucial matters should be prioritized: producing spawning broodstock and mass rearing of seeds. Milder research has been carried out in these two field areas,

Table 6
Effects of plant extracts on the environmental stress of crustaceans

Crustacean species	Plant extract	Optimal dose	Environmental stress treatment	Environmental stress indicators								Reference
				Survival	Hyaline cell	Granular cell	Haemocyte count	SOD activity	GPx	Lysozyme	PO	
Artemia	Indian ginseng, *W. somnifera* (R)	1000 mg/l*	Temperature (41 °C, 15 min)	●								Castro, 2022
	Indian ginseng, *W. somnifera* (R)	1000 mg/l*	pH (5.5, 24 h)	●								Castro, 2022
	Indian ginseng, *W. somnifera* (R)	1000 mg/l*	Salinity (100 ppt, 48 h)	●								Castro, 2022
White-leg shrimp, *L. vannamei*	Ginger, *Z. officinale* (rhizome)	1 g/kg	Ammonia (40 mg/L, 96 h)	●								Tu et al., 2023
	Red seaweed, *Gracilaria Tenuistipitata*	400 mg/l*	Temperature (28 °C, 120 h)		●	●	●	●				Yeh et al., 2010
	Mesquite, *Prosopis juliflora* (L)	50 mg/kg	Temperature (7 °C, 12 h)	●				●	●	●	●	Zabolinia et al., 2024
	Green algae, *Ulva ohnoi*	20 mg/kg	Temperature (11.5 °C, 1 h)	●								Coelho et al., 2023
	Noni, *Morinda citrifolia* (F)	15 ml/L**	Salinity (5 ppt, 96 h)	●								Phan et al., 2023
	Noni, *Morinda citrifolia* (F)	15 ml/L**	Ammonia (40 mg/L, 96 h)	●								Phan et al., 2023
	Red Seaweed, *Kappaphycus alvarezii*	0.5 g/L***	Salinity (0 ppt, 30 min)	●								Suantika et al., 2017
	Moringa, *Moringa oleifera* (L)	50 g/kg	Salinity (0 ppt, 24 h)	●								Baniesmaeili et al., 2023
	Moringa, *Moringa oleifera* (L)	50 g/kg	Salinity (55 ppt, 24 h)	●								Baniesmaeili et al., 2023

Note. F: fruit, L: leaf, R: root, GPx: glutathione peroxidase, PO: phenoloxidase, SOD: superoxide dismutase. Many of the crustaceans were given plant extract through feeding, while those given plant extract via immersion, spray and artemia enrichment are indicated by the symbol *, **, ***, respectively. The green circle indicates environmental stress indicator results that are better than those of the control treatment (without the plant extract) especially regarding seed production or, more specifically, the crustacean larval phase. Farmers often face barriers to increasing seed output because of the occurrence of larval mass mortalities caused by pathogen infection. Furthermore, researchers have yet to take the initiative to increase publications regarding plant efficacy on gonads for rapid reproduction during crustacean farming. Additionally, regarding spiny lobsters, past studies have poorly documented any implications of plants or herbs for the growth, reproduction or immunity of spiny lobsters, probably due to constraints in the researcher's ability to rear spiny lobsters while conducting an experiment. Currently, neither spiny lobster domestication nor spiny lobster landing from the fishery sector has fully recovered; in this context, researchers should commit to further participation in any research relevant to the relationship between plant additives and spiny lobster.

As a whole, several conditions should be taken into consideration before the commercialization of plants in the aquaculture industry, with the most important conditions encompassing plant efficacy and plant dosage. Additionally, this review explains the common process of obtaining plant extracts, starting with collection, followed by maceration, extraction and evaporation. Several techniques are then applied to introduce plant extracts into crustaceans via pellets, coatings, immersions or injections. Plants and herbs such as amaranth, soursop leaf, mulberry leaf, olive, cajuput, bitterweed, Shepherd's needle, Indian borage, Chinese skullcap, and Indian gooseberry have been verified to improve crustacean growth. A bioactive compound in plant extracts that resembles a moulting hormone, an ecdysteroid, may promote the growth of crustaceans through moulting stimulation. Bioactive compounds in plants also promote digestive enzyme secretion, intestinal morphology and the gut microbiota, which are crucial for better absorptive function, increasing appetite, and ultimately improving crustacean growth. Moreover, herbs such as common senduduk can promote ovarian maturation, ultimately resulting in the production of 100% spawned crustaceans. Compounds such as phytoestrogen, phytoecdysteroid and α-tocopherol might stimulate ovarian growth. Plants such as guava leaf, talt-silt mangrove leaf, tochu, chaihu, Indian ginseng, rosemary, mangrove cannonball tree, lechuguilla, moringa, neem, screw pine, Indian gooseberry, solanum, buton forest onion, roselle, giant sensitive tree and Tasmanian blue gum have been verified to contain phenolic compounds such as polyphenols, flavonoids, and tannins that have potent antimicrobial activity against several strains of bacteria while also promoting antioxidant defence mechanisms via CAT, GPx, GR, GST, GSH and SOD.

Knowledge gained from collected findings might drive more research to develop supplements or cures for increasing growth, reproduction, and immune systems to benefit crustacean farming since there is a pressing need to overcome rising issues, especially in curbing disease infections. Each plant has a specific function; for example, some plants or herbs may promote growth but are unable to strengthen the crustacean immune system, thus devaluing plants for development as pharmaceutical supplements. However, a combination of different plants may provide an impressive supplement or cure for the crustacean farming industry in the future. The development of well-balanced supplements is imperative, as they must be capable of performing different functions simultaneously. For example, we should prioritize plant additives that can enhance crustacean egg development and, at the same time, protect vulnerable eggs from disease infections since many crustaceans bear their eggs underneath their abdomen, which is susceptible to external pathogens.

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