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REVIEW

Microencapsulation of anthocyanins from *Rubus* spp. and *Ipomoea batatas* (L.) in ornamental aquaculture: a minireview of their use as a feed additive, influence on pigmentation, and technical relevance

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Abstract Ornamental aquaculture represents a multibillion-dollar global market based on the trade of aquatic organisms and products related to their breeding and maintenance. In this context, ornamental fish stand out due to their high economic and zootechnical relevance. The commercial value of ornamental fish is directly linked to their phenotypic characteristics, particularly skin colouration. However, a frequent reduction in pigmentation intensity is observed when fish are kept in culture or aquarium systems. As a strategy to mitigate this effect, dietary supplementation with natural additives has shown promise. Among these, natural pigments are relevant, especially anthocyanin compounds, which, in addition to affecting colouration, also promote physiological benefits to organisms, acting as antioxidants and metabolic modulators. Microencapsulation emerges as a technique to preserve the stability of these pigments against external environmental factors. This review addresses the use of bioactive compounds in aquaculture, the blackberry fruit (*Rubus* spp.) and the purple sweet potato tuber (*Ipomoea batatas* (*L.*)), the influence of anthocyanins on fish colouration, and the microencapsulation technique for natural anthocyanin pigments.

Keywords Antioxidants . Fish farming . Natural colours . Nutritional additives

Introduction

Industrial aquaculture is a growing segment of agribusiness and is part of a chain that, in addition to the

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production of aquatic organisms, involves issues of sustainability, water and human resources, investment, biosafety, and health (Marques et al. 2020). In developing countries, aquaculture plays an important role in food and nutritional security, income generation, and promoting local biodiversity, and preserving cultural traditions (Vissio et al. 2021).

Aquaculture encompasses all forms of aquatic organism farming, producing animals or plants in fresh, brackish, and/or marine (FAO 2015; Chiquito-Contreras et al. 2022). It also encompasses individual, corporate, or state ownership, in contrast to capture fisheries, where aquatic organisms are exploited as a common property source (Rana 1997; Brugere et al. 2023). Among the production, ornamental aquaculture has been gaining prominence, especially fish farming.

According to Valenti et al. (2021), more than 250 species of ornamental fish, invertebrates, and aquatic plants have been cultivated in Brazil. The ornamental freshwater fish farming is particularly prominent in the country's Southeast region, centered in the states of São Paulo and Minas Gerais. The production of more than 100 species has been reported in recent decades, fishe specimens that come from the Amazon basin and Asia, with millions of specimens sold annually in the domestic market. Among the species produced are the angelfish (*Pterophyllum scalare*), discus (*Symphysodon aequifasciatus*), betta (*Betta splendens*), kinguio (*Carassius auratus*), nishikigoi or koi carp (*Cyprinus carpio*), and guppy (*Poecilia reticulata*).

The demand for ornamental fish has been growing, as it is part of an expanding economic activity. In general, the value of commercialized fish increases according to their morphology and colouration. Therefore, the development of techniques for the production and maintenance of these fish is essential. Key techniques in this context include nutritional supplementation (such as the supply of carotenoids), stocking density control, and the maintenance of adequate environmental parameters (Kaur and Shah 2017; Rashidian et al. 2021; Lau et al. 2023), among others.

In this context, the inclusion of food additives in the diet of ornamental fish can reduce costs, promote welfare responses, decrease oxidative activity, alter colouration, and improve fish growth and health (Vanegas-Espinoza et al. 2019; Rashidian et al. 2021; Rekha et al. 2024). Among the various food additives, natural dyes stand out, which can act directly on chromatophores, playing a fundamental role in the dynamics of fish colouration and altering the colour pattern displayed (Scárdua et al. 2024). Among these natural dyes, anthocyanin pigments stand out for their ability to stimulate colouration and, possibly, promote the health and well-being of ornamental fish.

The main source of widely used fish skin pigmentation is carotenoids. However, anthocyanins, in addition to their beneficial effects on the health and nutrition of humans and animals, are also used to improve fish colouration (Monika et al. 2019; Linh et al. 2022). Among the natural sources of anthocyanins, the blackberry fruit (*Rubus* spp.) (Zielinski et al. 2015; Memete et al. 2023) and the purple sweet potato tuber (*Ipomoea batatas* (L.)) stands out (Li et al. 2019; de Barros et al. 2024b).

To increase the effectiveness of anthocyanin pigments in fish organisms, one alternative is the microencapsulation of these compounds. This technique is widely used to protect the bioactive compounds present in natural dyes, ensuring greater stability and bioavailability. However, despite its potential, there are still few references on the application of anthocyanin microencapsulation in diets for ornamental fish, as highlighted by Sukardi et al. (2018) and Vanegas-Espinoza et al. (2019).

Bioactive compounds used in ornamental fish feed

In Brazil, the regulation of the use of additives for animal feed is carried out by Normative Instructions Nº. 13 of November 30, 2004, and Nº. 3 January 25, 2021, of the Ministry of Agriculture and Livestock (MAPA). Defining additives as any substance, microorganism, or formulated product, intentionally added to products and/or diet, which are not normally used as ingredients, but which improve or affect the characteristics of the products and/or animal performance (Diário Oficial Da União, IN nº 3 de 25/01/2021; IN nº13 de 30/11/2004).

The use of additives in aquaculture has been highlighted for promoting a series of advantages, such as increased productivity, improved diet palatability, reduced mortality, strengthened immunity, and optimized feed conversion (Porto et al. 2020; Cardoso et al. 2021). In ornamental aquaculture, in addition to the benefits already mentioned, additives are widely used to improve the morphological appearance of fish, with an emphasis on intensifying colouration, a crucial factor for the commercial value of these species (Honorato et al. 2021; Singh et al. 2021; Lau et al. 2023).

Table 1 presents the studies on the use of bioactive compounds, microencapsulation techniques, and the main findings in ornamental aquaculture, as presented in this article.

In a study by Ebeneezar et al. (2020), experimental diets were supplemented with natural oleoresin pigments from paprika, turmeric, chlorophyll, and their combinations at a concentration of 20 $g.kg^{-1}$ to increase skin pigmentation in clownfish (*Amphiprion ocellaris*). After 60 days of supplementation, the additives affected the intensity of skin colour for shades of red and yellow, with paprika oleoresin being considered superior. In addition to colouration, the parameters of final body weight, specific growth rate, percentage of weight gain, and feed efficiency were also affected by the additives, in which the diet with the combinations stood out, followed by the diet containing paprika.

Using the hydroalcoholic extract of jabuticaba (*Plinia cauliflora*) peel (HEJ) in *Betta splendens* diets, the effects on antioxidant activity, growth index, and colouration were evaluated. Diets supplemented with HEJ at concentrations of 0.5, 1, 1.5, and 2 $g.kg^{-1}$ were provided, in addition to a control group. After 21 days of supplementation, a reduction in superoxide dismutase activity was observed in the skin of the groups fed with 1.5 and 2 $g.kg^{-1}$ of HEJ compared to the others. In addition, there was an increase in feed conversion efficiency and an increase in the brightness of the fish colouration. It was concluded that supplementation with 2 $g.kg^{-1}$ of hydroalcoholic extract of jabuticaba peel (HEJ) provides an antioxidant effect, reflected in

Table 1 Studies on the use of bioactive compounds and microencapsulation in ornamental fish farming

Topic / Bioactive compound	Source / Additive	Species of fish	Main findings	Reference
Pigments Sources of Carotenoids	Natural Carotenoids (beet, carrot, and tomato)	Koi Carp (*Cyprinus carpio*)	Improved growth and colouration; mixture of sources was more effective.	Maiti et al. (2017)
	Paprika, Turmeric, and Chlorophyll Oleoresin	Clown fish (*Amphiprion ocellaris*)	Higher intensity of red and yellow; improved zootechnical performance.	Ebeneezar et al. (2020)
Anthocyanin Sources	Co-stabilized Anthocyanin Extract (red cabbage and beet peel)	Orange sword tail fish (*Xiphophorus helleri*)	Intense red colouration; viability as a pigment source.	Monika et al. (2019)
	Roselle Anthocyanins (*Hibiscus sabdariffa*)	Goldfish (*Carassius auratus*)	Improved growth and colouration.	Vanegas-Espinoza et al. (2019)
	Hydroalcoholic extract of Jabuticaba (EHJ)	Betta (*Betta splendens*)	Increase in blue colouration brightness; antioxidant effect.	França et al. (2022)
	Hydroalcoholic roselle extract (HER)	Mato-Grosso (*Hyphessobrycon eques*)	Enhanced red pigmentation; better zootechnical and enzymatic parameters.	Cruz et al. (2023)
Non-Conventional Sources (Aquatic Plants)	Duckweed Meal (*Lemna minor*)	Rainbow Trout (*Oncorhynchus mykiss*)	Reported as a sustainable source of proteins and carotenoids.	Fiordelmondo et al. (2022)
	Algal Meal (*Spirulina* sp. and *Chlorella vulgaris*)	Rainbow Trout (*Oncorhynchus mykiss* W.)	50% substitution of fishmeal enhanced growth performance and histological indices.	Velichkova et al. (2024)
Microencapsulation Technique	β-estradiol (hormones), Lysine (amino acid), and vitamin C	Gilthead seabream (*Sparus aurata*) and Senegal sole (*Solea senegalensis* Kaup)	Protein-based microcapsules; Findings demonstrate the feasibility of these microencapsulated particles.	Yúfera et al. (2003)
	Oxytetracycline	Zebrafish (*Danio rerio*) and Goby (*Asterropteryx semipunctata*)	Lipid-based spray-dried microcapsules; The method effectively enabled antibiotic administration.	Temple and Langdon (2009)
	Masculinizing hormone (17-α-methyltestosterone)	Nile tilapia (*Oreochromis niloticus*)	*Spray-dried* micro-bound or microencapsulated diets, with or without coating material; The technique was successfully applied to achieve sex reversal;	Honorato et al. (2012)
	Roselle Anthocyanins (*Hibiscus sabdariffa*)	Goldfish (*Carassius auratus*)	Microencapsulated anthocyanins; The method proved effective in supplying pigments.	Vanegas-Espinoza et al. (2019)
	Selenium (Se)	Nile tilapia (*Oreochromis niloticus*)	Selenium-loaded chitosan nanoparticles; The method effectively delivered selenium, improving growth performance, feed utilization, oxidative status, and antioxidant response.	Araujo et al. (2021)
	Probiotic	Nile tilapia (*Oreochromis niloticus*)	Microencapsulated probiotics; The technique enhanced production performance and health indicators, confirming immunomodulatory probiotic effects.	de Moraes et al. (2022)

*Note: Some included studies use model species or commercial aquaculture species to demonstrate the effectiveness of principles and techniques that are directly applicable to ornamental aquaculture.

a greater brightness of the colouration of blue *Betta splendens* (França et al. 2022).

In the study carried out by Maiti et al. (2017) with koi carp (*Cyprinus carpio*), a 45-day feeding trial was conducted to evaluate the improvement in colouration and growth parameters. The diets were supplemented with 1% natural carotenoids, obtained from beet root powder, carrot peel powder, tomato peel powder, and a mixture of these ingredients (mix), totalling five experimental diets. The study demonstrated that natural carotenoids were effective in improving growth and colour parameters with the inclusion of 1% in the diet. However, among all the diets tested, the mixture of natural carotenoids was the most effective in increasing growth parameters and intensifying the skin colour of koi carp.

Cruz et al. (2023) evaluated the effects of including the hydroalcoholic extract of rosella (*Hibiscus sabdariffa*) in the diets of the Mato Grosso fish (*Hyphessobrycon eques*). Diets supplemented with hydroalcoholic extract of rosella (HER) at concentrations of 0.12, 0.25, and 0.50 mg of HER/kg of feed were tested, in addition to a control group. The results demonstrated that the inclusion of 0.25 and 0.50 HER/kg promoted improvements in zootechnical indices, standard length, and feed efficiency. Regarding colouration, the fish showed changes in chroma (shades of green and red), with a tendency towards an increase in the red hue. Furthermore, the use of 0.25 and 0.50 mg of HER/kg resulted in a reduction in the activity of the enzymes alanine aminotransferase (ALT) and aspartate aminotransferase (AST), while there was an increase in catalase activity at higher concentrations of the extract. Thus, the hydroalcoholic extract of rosella proved to be effective in feeding the Mato Grosso fish at a concentration of 0.50 mg of HER/kg.

It is important to highlight that aquatic plants, natural components of the ecosystems where ornamental species originate, represent a sustainable and still underutilized source of bioactive compounds (Omweno et al. 2024; Sumana et al. 2025). Species such as duckweed (*Lemna minor*) (Fiordelmondo et al. 2022), macroalgae and microalgae (e.g., *Spirulina* and *Chlorella*) (Ringø et al. 2025; Nahavandi and Razmi 2025) are rich in proteins, lipids, minerals, carotenoids, antioxidants, β-carotene, xanthophyll, and polysaccharides (Fiordelmondo et al. 2022; Ringø et al. 2025; Nahavandi and Razmi 2025). The inclusion of these resources in feeds can fill a significant gap in ornamental fish nutrition, offering a natural and low-cost alternative to conventional synthetic additives.

Velichkova et al. (2024), aiming to reduce the use of fishmeal in rainbow trout (*Oncorhynchus mykiss* W.) feeds, investigated the partial and total replacement of fishmeal with an algae meal composed of *Spirulina* sp. and *Chlorella vulgaris*. The study aimed to evaluate the effects of 50% and 100% replacement rates on fish growth, histological parameters, and fillet quality. At the end of the experimental period, the replacements positively influenced hydrochemical parameters. The highest average live weight was measured in rainbow trout fed a diet containing 50% algae meal. In this same group, hepatocytes exhibited larger fat droplets, and their nuclei were located in the peripheral zone of the cells. Furthermore, replacing fishmeal with 50% algae meal in the feed resulted in a 36.44% reduction in the lipid content of rainbow trout fillets compared to the control fish. It is concluded that a diet with 50% algae meal is sufficient to improve the values of the histological structures studied in the fish intestines.

Therefore, it is possible to verify that several additives added to the diet of ornamental fish are effective in positively altering zootechnical parameters, skin colour, feed efficiency, antioxidants, and digestive enzymes.

***Rubus* spp.**

Blackberries (*Rubus* spp.) belong to the large group of plants in the genus *Rubus*. This genus belongs to the *Rosaceae* family, which is of great importance for Brazilian fruit growing (Facchinello et al. 1994; Daubeny 1996; Antunes 2002, 2006; Jacques and Zambiazi 2011; Vizzotto et al. 2012; Martins et al. 2023). This fruit species has an erect or creeping habit, producing aggregated fruits, which are formed by small drupes, weighing about four to seven grams, black in colour when ripe, and with an acidic to sweet-acid flavour. Its main commercial cultivars have thorns, which require the harvester to be very careful with their physical integrity, as well as the quality of the fruit (Jacques and Zambiazi 2011; Vizzotto et al. 2012; Martins et al. 2023).

The *in natura* blackberry is highly nutritious, containing approximately 85% water, 10% carbohydrates, and a high amount of minerals, calcium, B vitamins, and vitamin A. It can be consumed fresh or used in the production of processed products, such as juice, ice cream, yogurt, jams, and creamy sweets. It is a fruit that has been attracting the attention of producers and consumers, as it has a high content of bioactive compounds in its composition (Poling 1997; Antunes 2002, 2006; Bowen-Forbes et al. 2010; Wu et al. 2010, 2021; Jacques and Zambiazi 2011; Vizzotto et al. 2012; Martins et al. 2023).

Among these bioactive compounds, blackberries contain phenolic compounds, tocopherols, ascorbic acid, and carotenoids, which are phytochemicals with antioxidant action (Wang and Jiao 2000; Jacques and Zambiazi 2011; Martins et al. 2023). Among fresh fruits, blackberries have the highest concentrations of antioxidants ever studied (Jacques and Zambiazi 2011; Kaume et al. 2012; Rotili et al. 2022; Martins et al. 2023), with a high concentration of phenolic compounds, with emphasis on the high levels of anthocyanins, which exceed the levels observed in strawberries (Wang and Jiao 2000; Zielinski et al. 2015; Wu et al. 2021; Rotili et al. 2022; Martins et al. 2023). It presents antioxidant activity against superoxide radicals (O_2^-), hydrogen peroxide (H_2O_2), hydroxyl (OH), and singlet oxygen (O_2) (Wang and Jiao 2000; Jacques and Zambiazi 2011; Wu et al. 2021; Rotili et al. 2022; Martins et al. 2023) .

The presence of ellagic acid, a phenolic compound with antioxidant, antimutagenic, anticancer, and potent inhibitor of chemical induction of cancer, has also been reported (Maas et al. 1991; Wang et al. 1995; Antunes, 2002 2006; Jacques and Zambiazi 2011; Vizzotto and Pereira 2011; Vizzotto et al. 2012; Wu et al. 2021; Martins et al. 2023). Blackberries also contain an abundant soluble fiber, pectin, which acts to reduce blood cholesterol levels, preventing cardiovascular and circulatory diseases (Ness and Powles 1997; Antunes 2002; Stoclet et al. 2004; Vizzotto and Pereira 2011; Wu et al. 2021; Martins et al. 2023).

In Brazil, the main producing state is Rio Grande do Sul. However, there is high production potential in temperate and subtropical regions due to its adaptability and potential to achieve high productivity. It can be implemented in the states of São Paulo, Paraná, Santa Catarina, and in the south of Minas Gerais. Due to its low cost of implementation and maintenance of the orchard, but mainly due to the reduced use of agricultural pesticides, it becomes an option for family farming, enabling the achievement of high economic returns (Antunes 2002, 2006; Antunes and Rasseira 2004; Jacques and Zambiazi 2011; Rotili et al. 2022).

Ipomoea batatas (L.)

Purple sweet potato (*Ipomoea batatas* (L.)), is a creeping dicotyledonous plant, considered a perennial herb. It is scientifically classified in Kingdom Plantae, Division Magnoliophyta, Class Magnoliopsida, Order Solanales, Family *Convolvulaceae*, Genera: *Ipomoea*, and Species: *potatoes* (Bovell-Benjamin 2007; Mohanraj and Sivasankar 2014; Li et al. 2019; Rosell et al. 2024).

The root is popularly known as the purple sweet potato (Fan et al. 2008; Zhang et al. 2009; Amaro et al. 2017; Sánchez et al. 2019; Im et al. 2021) or purple-fleshed sweet potato (Yoshimoto et al. 2001; Bridgers et al. 2010; Xu et al. 2015; Rosell et al. 2024).

Purple sweet potato is rich in dietary fiber, minerals, vitamins, polysaccharides, and antioxidants such as phenolic acids, anthocyanins, tocopherol, and β-carotene, and can be used by humans and animals (Simmonds 1993; Teow et al. 2007; Xu et al. 2015; Im et al. 2021; Rosell et al. 2024). It has a red-purple colour, high anthocyanin content, high total phenol content, and high antioxidant activity (Li et al. 2019; de Barros et al. 2024b). The purple colour of purple sweet potato is achieved due to the presence and form of anthocyanins (Zhao et al. 2013; de Barros et al. 2024a, b).

Li et al. (2019) reported that the functional activities of purple sweet potato anthocyanins include antioxidant, antimutagenic, antitumor, and liver protection activities, where the natural edible pigment of purple sweet potatoes is safe, non-toxic, odorless, bright in colour, and has the advantages of high-yield, low cost, rich nutrition, better light and heat stability, and certain pharmacological effects. It also has broad application prospects in the food, cosmetics, medicine, and aquaculture products industries.

The anthocyanin content of purple sweet potatoes is significantly higher than that of white, yellow, and orange-fleshed sweet potatoes (Fan et al. 2008; Li et al. 2019; Wang et al. 2024). Numerous studies have shown that the stability is dependent on several factors, including pigment structure and concentration, pH, and temperature in the extraction process (Fan et al. 2008; de Barros et al. 2024a, b).

The chemical structure of purple sweet potato anthocyanins is mainly composed of cyanidins and peonidins in the form of monoacylation and diacylation, which, due to the presence of the acylation form, makes purple sweet potato anthocyanins more thermally stable and provides ultraviolet resistance (Li et al. 2019;

Tang et al. 2023; Rosell et al. 2024; Wang et al. 2024).

Influence of anthocyanins on fish colouration

Fish colouration in ornamental aquaculture is one of the determining factors for consumer enthusiasm and market demand across the planet (Sathyaruban et al. 2021; Lau et al. 2023; Scárdua et al. 2024). Colouration variation in fish is exhibited through the expression of dermal chromatophores, such as melanophores, xanthophores, erythrophores, iridophores, leucophores, and cyanophores, which contain different pigments. In vertebrates, the main pigments responsible for promoting colouration in the dermis are melanins, pteridines, carotenoids, and anthocyanins. Melanin and pteridine pigments are synthesized by animals, while carotenoids and anthocyanins are not biosynthesized by animals, therefore, dietary carotenoids and anthocyanins in natural or synthetic forms must be added to the diet for fish to achieve their colourations (Vanegas-Espinoza et al. 2019; Sathyaruban et al. 2021; Cruz et al. 2023; Lau et al. 2023; Scárdua et al. 2024).

Anthocyanins are phytogenic bioactive compounds that are widely present in fruits, vegetables, leaves, flowers, grains, and roots, where at least 653 anthocyanins are found in nature. They are hydrophilic pigments that make up a subgroup of flavonoids. They are glycosidic forms of anthocyanidins, and their molecule has a diphenylpropane skeleton (C6C3C6) and exhibits red, purple, or blue colour, depending on the pH (Figure 1). Among the anthocyanins, those commonly found are cyanidin, delphinidin, and pelargonidin, or their methylated derivatives, that is, malvidin, peonidin, and petunidin (Figure 2) (Mota 2006; Zielinski et al. 2015; Linh et al. 2022; de Barros et al. 2024a; Guo and Shahidi 2024).

In our previous research, under the title "Anthocyanin extraction methods: synthesis of morpho-anatomical knowledge for decision-making based on decision-tree" (de Barros et al. 2024a), Figures 1 and 2 were made for better understanding and used in this article.

Anthocyanins have a variety of beneficial effects in animals and humans, including antioxidant, anti-inflammatory, antimicrobial, and anticancer activities, used for the treatment of oxidative damage in the

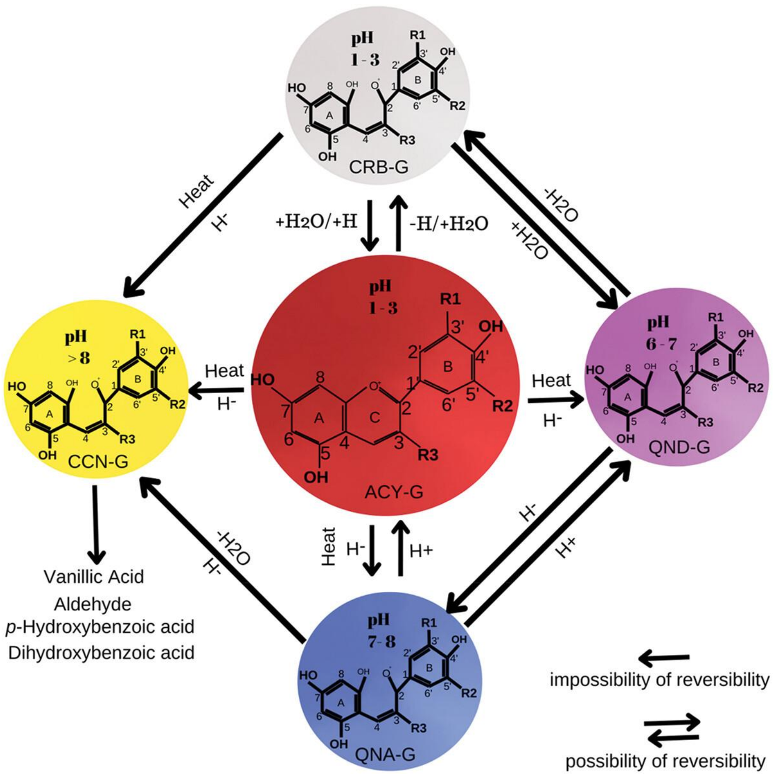

Fig. 1 Changes in anthocyanin characteristics by temperature, pH, Hydroxyl (OH), and Water (H_2O). Figure from the study by De Barros et al. (2024a). ACY-G (anthocyanin glycoside), CRB-G (Carbidol glycoside), QND-G (Khenidal glycoside), QNA-G (Anionic kenoidal glycoside), CCN-G (Chalcone glycoside).

liver and hyperglycemia, and also for the prevention of cardiovascular diseases, in addition to inhibiting the activity of free radicals and reducing inflammation and aging (Yilmaz 2019; Linh et al. 2022; Ijinu et al. 2023).

In a study carried out with orange sword tail fish (*Xiphophorus helleri*), the effects of dietary incorporation of co-stabilized anthocyanin pigment extract from red cabbage and biological waste from beet peel (concentration of 400 mg.kg^{-1}) were evaluated to improve colouration and growth. The results after 45 days of feeding indicated high-intense red colouration in the treatments supplemented with anthocyanins. No significant variation was observed for growth parameters between treatments. The study indicated the possibility of using anthocyanin extracts as one of the biological sources of pigment to improve the colouration of orange scabbardfish (J. et al. 2019).

Microencapsulation of natural dyes

To increase the effectiveness of anthocyanin pigments in fish diets, one alternative is the microencapsulation of these pigments. One of the main disadvantages of natural pigments is their instability, which is influenced by environmental factors such as light, oxygen, pH, and temperature. However, an advantage is their solubility in water, which facilitates degradation during the feeding and storage process (Zhao et al. 2008; Özkan and Bilek 2014; Vanegas-Espinoza et al. 2019; Mohammadalinejhad and Kurek 2021; Sia et al. 2025).

Microencapsulation in fish diets results in a lower leaching rate of feed compounds, enabling the use of ingredients with better nutritional quality, providing better nutrition and ensuring better responses from the animals, reducing the possibility of contamination to people handling the diet, as well as to the environment (Honorato et al. 2012, 2016; Araujo et al. 2021; de Moraes et al. 2022).

Thus, the microencapsulation technique has been used for several years, with the aim of protecting bioactive compounds (Vanegas-Espinoza et al. 2019; Mohammadalinejhad and Kurek 2021; de Moraes et al. 2022), enabling the release of attractive substances, and conserving nutrients (Honorato et al. 2016; de Moraes et al. 2022). This technique can be performed in several ways, including simple or complex coace-

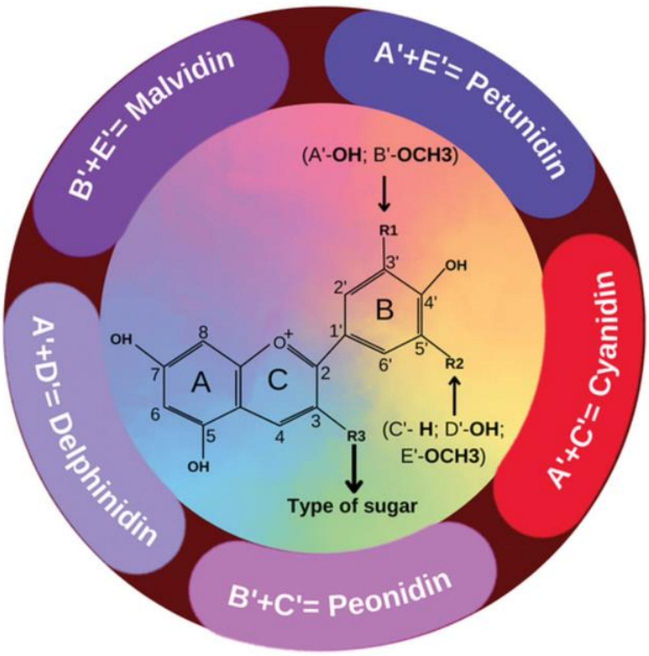

Fig. 2 Five common types of anthocyanins. Figure from the study by De Barros et al. (2024a). These structures showed the presence of A,' B,' C,' D,' and E', which correspond to OH, OCH_3, H, OH, and OCH_3, respectively, in R1 and R2. Cyanidin is formed by the combination of A' and C', while peonidin is formed by the combination of B' and C.' Delphinidin is formed by the combination of A' and D' and malvidin is formed by the combination of B' and E.' Petunidin is formed by the combination of A' and E. ' The type of sugar present in the anthocyanin molecule is defined by the position of R3.

rvation, ionic gelation, spray-drying, among others (Yúfera et al. 2003; Honorato et al. 2016; Mohammadalinejhad and Kurek 2021). Among these techniques, spray-drying is the most used in the pharmaceutical and food industries due to its versatility and relatively low cost (Vanegas-Espinoza et al. 2019; Mohammadalinejhad and Kurek 2021; de Barros et al. 2024a).

An important decision in the microencapsulation procedure is the choice of material for the microcapsule wall and the spray-drying conditions, which are key factors for the size, morphology, encapsulation efficiency, and stability of the core material. Among the wall material options, maltodextrins and starches stand out (Vanegas-Espinoza et al. 2019; de Moraes et al. 2022; Zarantoniello et al. 2024; de Barros et al. 2024b).

According to Vanegas-Espinoza et al. (2019), maltodextrin forms a good film during atomization, with rapid crust formation around the core material, which prevents its degradation or volatilization during the drying process. With high water solubility and low viscosity, maltodextrin has potential for application in the aquaculture industry, especially in the microencapsulation of food additives.

Microencapsulated diets have demonstrated greater efficacy compared to microagglutinated or mashed diets in the transport of biologically important substances, such as the hormone estradiol (Yúfera et al. 2003), oxytetracycline (Temple and Langdon 2009), testosterone (Honorato et al. 2012), selenium (Araujo et al. 2021), and probiotics (de Moraes et al. 2022). Therefore, diets produced by this process may enable the use of additives for ornamental aquaculture.

Conclusion

It is concluded that the use of microencapsulated blackberry or purple sweet potato anthocyanins for ornamental fish diets presents technical and biological viability, representing a sustainable alternative for maintaining the colouration and health of organisms in cultivation systems.

List of abbreviations

HEJ - Hydroalcoholic Extract of Jabuticaba Peel
HER - Hydroalcoholic Extract of Rosella

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References

Amaro GB, Fernandes FR, Silva GO, Mello AFS, Castro LAS (2017) Desempenho de cultivares de batata doce na região do Alto Paranaíba-MG. Hortic Bras 35:286–291. https://doi.org/10.1590/s0102-053620170221

Antunes LEC (2006) Amora-preta (*Rubus* spp.). Rev Bras Frutic 28:339–558

Antunes LEC (2002) Amora-preta: nova opção de cultivo no Brasil. Ciência Rural 32:151–158. https://doi.org/10.1590/s0103-84782002000100026

Antunes LEC, Rasseira M do CB (2004) Aspectos técnicos da cultura da amora-preta. Embrapa Clima Temperado. Documentos, 122, Pelotas

Araujo JM, Fortes-Silva R, Pola CC, Yamamoto FY, Gatlin DM, Gomes CL (2021) Delivery of selenium using chitosan nanoparticles: synthesis, characterization and antioxidant and growth effects in Nile tilapia (*Oreochromis niloticus*). PLoS One 16:e0251786. https://doi.org/10.1371/journal.pone.0251786

Bovell-Benjamin AC (2007) Sweet potato: a review of its past, present and future role in human nutrition. Adv Food Nutr Res 52:1–59. https://doi.org/10.1016/S1043-4526(06)52001-7

Bowen-Forbes CS, Zhang Y, Nair MG (2010) Anthocyanin content, antioxidant, anti-inflammatory and anticancer properties of blackberry and raspberry fruits. J Food Compos Anal 23:554–560. https://doi.org/10.1016/j.jfca.2009.08.012

Bridgers EN, Chinn MS, Truong V-D (2010) Extraction of anthocyanins from industrial purple-fleshed sweetpotatoes and enzymatic hydrolysis of residues for fermentable sugars. Ind Crops Prod 32:613–620. https://doi.org/10.1016/j.indcrop.2010.07.020

Brugere C, Bansal T, Kruijssen F, Williams M (2023) Humanizing aquaculture development: putting social and human concerns at the center of future aquaculture development. J World Aquac Soc 54:482–526. https://doi.org/10.1111/jwas.12959

Cardoso AJ da S, dos Santos WV, Gomes JR, Martins MTS, Coura RR, Oliveira MG de A, Salaro AL, Ferreira P de MF, Carneiro APS, Zuanon JAS (2021) Ginger oil, zingiber officinale, improve palatability, growth and nutrient utilisation efficiency in Nile tilapia fed with excess of starch. Anim Feed Sci Technol 272:114756. https://doi.org/10.1016/j.anifeedsci.2020.114756

Chiquito-Contreras RG, Hernandez-Adame L, Alvarado-Castillo G, Martínez-Hernández M de J, Sánchez-Viveros G, Chiquito-Contreras CJ, Hernandez-Montiel LG (2022) Aquaculture—production system and waste management for agriculture fertilization—a review. Sustainability 14:7257. https://doi.org/10.3390/su14127257

Cruz BL da, Scardua MP, Sousa RM, Siqueira MS, Gimênes Junior H, Ziemniczak HM, Pause AG da S, Braz PH (2023) Extrato hidroalcoólico de rosela (*Hibiscus sabdariffa* L.) na alimentação do peixe Mato Grosso (*Hyphessobrycon eques*). Medicina Veterinaria (Brazil) 17:114–118. https://doi.org/10.26605/medvet-v17n2-5337

Daubeny HA (1996) Brambles. In: Janick J, Moore JN (eds) Fruit Breeding. Wiley, London, pp 109–190

de Barros GL, Silva FTS, Teixeira RS, Wagner JG, Rombaldi CV, Vizzotto M, Ubeyitogullari A, Nora L (2024a) Anthocyanin extraction methods: synthesis of morpho-anatomical knowledge for decision-making based on decision-tree. Int J Food Prop 27:1315–1346. https://doi.org/10.1080/10942912.2024.2409893

de Barros GL, Tuhanioglu A, Kaur S, Nora L, Ubeyitogullari A (2024b) Extraction of anthocyanins from purple sweet potato using supercritical carbon dioxide and conventional approaches. Appl Food Res 4:100505. https://doi.org/10.1016/j.afres.2024.100505

de Moraes AV, Owatari MS, da Silva E, de Oliveira Pereira M, Piola M, Ramos C, Farias DR, Schleder DD, Jesus GFA, Jatobá A (2022) Effects of microencapsulated probiotics-supplemented diet on growth, non-specific immunity, intestinal health and resistance of juvenile Nile tilapia challenged with *Aeromonas hydrophila*. Anim Feed Sci Technol 287:115286. https://doi.org/10.1016/j.anifeedsci.2022.115286

Diário Oficial da União (2021) Instrução normativa mapa Nº 3, de 25 de janeiro de 2021. Ministério da Agricultura e Pecuária - MAPA 1:1–3

Diário Oficial da União (2004) Instrução normativa Nº 13, de 30 de novembro de 2004. Ministério da Agricultura e Pecuária - MAPA 1–10

Ebeneezar S, Prabu DL, Chandrasekar S, Tejpal CS, Madhu K, Sayooj P, Vijayagopal P (2020) Evaluation of dietary oleoresins on the enhancement of skin coloration and growth in the marine ornamental clown fish, *Amphiprion ocellaris* (Cuvier 1830). Aquaculture 529:. https://doi.org/10.1016/j.aquaculture.2020.735728

Facchinello JC, Hoffmann A, Santos AM dos (1994) Amoreira-preta, framboesa e mirtilo: pequenos frutos para o sul do Brasil. In: 13º congresso brasileiro de fruticultura. Sociedade Brasileira de Fruticultura, Salvador, pp 989–990

Fan G, Han Y, Gu Z, Chen D (2008) Optimizing conditions for anthocyanins extraction from purple sweet potato using response surface methodology (RSM). LWT - Food Sci Technol 41:155–160. https://doi.org/10.1016/j.lwt.2007.01.019

FAO (2015) Aquaculture: Junior Farmer Field and Life School-Facilitator's guide. Roma

Fiordelmondo E, Ceschin S, Magi GE, Mariotti F, Laffaldano N, Galosi L, Roncarati A (2022) Effects of partial substitution of conventional protein sources with duckweed (*Lemna minor*) meal in the feeding of rainbow trout (*Oncorhynchus mykiss*) on growth performances and the quality product. Plants 11:1220. https://doi.org/10.3390/plants11091220

França GB, Siqueira MS, Melo JC de S, de Albuquerque DT, Venturini FP, Honorato CP (2022) Hydroalcoholic extract of jabuticaba peel in the diet of betta fish. Boletim do Instituto de Pesca 48:1–7. https://doi.org/10.20950/1678-2305/BIP.2022.48.E659

Guo F, Shahidi F (2024) Can anthocyanins replace antibiotics in food and animal feed? a review. Trends Food Sci Technol 143:104219. https://doi.org/10.1016/j.tifs.2023.104219

Honorato CA, Dorce LS, Ziemniczak HM, Vasconcelos FAB, Santos SP dos (2021) Bioativos de plantas do cerrado na alimentação de peixes ornamentais. In: Nora FMD (ed) Compostos Bioativos e suas Aplicações. Mérida Publishers, pp 226–236

Honorato CA, Jomori RK, Carneiro DJ (2016) Crescimento e sobrevivência de larvas de pacu (*Piaractus mesopotamicus*) alimentadas com microdietas. Revista Brasileira de Ciência Veterinária 23:71–75. https://doi.org/10.4322/rbcv.2016.033

Honorato CA, Tesser MB, Portella MC, Carneiro DJ (2012) Microdietas na alimentação da tilápia do Nilo durante a fase de reversão sexual. Nucleus Animalium 4:27–36. https://doi.org/10.3738/1982.2278.651

Ijinu TP, De Lellis LF, Shanmugarama S, Pérez-Gregorio R, Sasikumar P, Ullah H, Buccato DG, Di Minno A, Baldi A, Daglia M (2023) Anthocyanins as immunomodulatory dietary supplements: a nutraceutical perspective and micro-/nano-strategies for enhanced bioavailability. Nutrients 15:4152. https://doi.org/10.3390/nu15194152

Im YR, Kim I, Lee J (2021) Phenolic composition and antioxidant activity of purple sweet potato (*Ipomoea batatas* (L.) Lam.): varietal comparisons and physical distribution. Antioxidants 10:462. https://doi.org/10.3390/antiox10030462

Monika J, Neelakantan V, Seenappa D (2019) Effect of dietary incorporation of anthocyanin pigments on the coloration and growth of orange sword tail fish (*Xiphophorus helleri*). Int J Fish Aquat Stud 7:144–149

Jacques AC, Zambiazi RC (2011) Fitoquímicos em amora-preta (*Rubus* spp.). Semin Cienc Agrar 32:245–260

Kaume L, Howard LR, Devareddy L (2012) The blackberry fruit: a review on its composition and chemistry, metabolism and bioavailability and health benefits. J Agric Food Chem 60:5716–5727. https://doi.org/10.1021/jf203318p

Kaur R, Shah TK (2017) Role of feed additives in pigmentation of ornamental fishes. Int J Fish Aquat Stud 5:684–686. https://doi.org/10.1371/journal.pone.0162410

Lau CC, Mohd Nor SA, Tan MP, Yeong YS, Wong LL, Van de Peer Y, Sorgeloos P, Danish-Daniel M (2023) Pigmentation enhancement techniques during ornamental fish production. Rev Fish Biol Fish 33:1027–1048. https://doi.org/10.1007/s11160-023-09777-4

Li A, Xiao R, He S, An X, He Y, Wang C, Yin S, Wang B, Shi X, He J (2019) Research advances of purple sweet potato anthocyanins: extraction, identification, stability, bioactivity, application and biotransformation. Molecules 24:1–21. https://doi.org/10.3390/molecules24213816

Linh NV, Nguyen D Van, Khongdee N, Wannavijit S, Outama P, Le Xuan C, Mahatheeranont S, Sookwong P, Le TD, Hoseinifar SH, Moon Y-H, Van Doan H (2022) Influence of black rice (*Oryza sativa* L.) bran derived anthocyanin-extract on growth rate, immunological response, and immune-antioxidant gene expression in Nile tilapia (*Oreochromis niloticus*) cultivated in a biofloc system. Fish Shellfish Immunol 128:604–611. https://doi.org/10.1016/j.fsi.2022.08.041

Maas JL, Galletta GJ, Stoner GD (1991) Ellagic acid, an anticarcinogen in fruits, especially in strawberries: a review. HortScience 26:10–14

Maiti MK, Bora D, TL N, Sahoo S, BK A, Kumar S (2017) Effect of dietary natural carotenoid sources on colour enhancement of koi carp, *Cyprinus carpio* L. Int J Fish Aquat Stud 5:340–345

Marques FB, Watterson A, Rocha AF, Cavalli LS (2020) Overview of brazilian aquaculture production. Aquac Res 51:4838–4845.

https://doi.org/10.1111/are.14828

Martins MS, Gonçalves AC, Alves G, Silva LR (2023) Blackberries and mulberries: berries with significant health-promoting properties. Int J Mol Sci 24:12024. https://doi.org/10.3390/ijms241512024

Memete AR, Sărac I, Teusdea AC, Budău R, Bei M, Vicas SI (2023) Bioactive compounds and antioxidant capacity of several blackberry (*Rubus* spp.) fruits cultivars grown in Romania. Horticulturae 9:556. https://doi.org/10.3390/horticulturae9050556

Mohammadalinejhad S, Kurek MA (2021) Microencapsulation of anthocyanins—critical review of techniques and wall materials. Appl Sci 11:3936. https://doi.org/10.3390/app11093936

Mohanraj R, Sivasankar S (2014) Sweet potato (*Ipomoea batatas* [L.] Lam) - a valuable medicinal food: a review. J Med Food 17:733–741. https://doi.org/10.1089/jmf.2013.2818

Mota RV da (2006) Caracterização do suco de amora-preta elaborado em extrator caseiro. Ciência e Tecnologia de Alimentos 26:303–308. https://doi.org/10.1590/S0101-20612006000200012

Nahavandi R, Razmi K (2025) A comprehensive review of macroalgae and microalgae synergies: impacts on growth, development, and immune functions in aquatic animals. Int J Vet Res 5:115–123

Ness AR, Powles JW (1997) Fruit and vegetables, and cardiovascular disease: a review. Int J Epidemiol 26:1–13. https://doi.org/10.1093/ije/26.1.1

Omweno JO, Argwings O, Sieberi BM, Angima M, Ondieki PM (2024) Utilization of aquatic plants and microalgae for sustainable aquaculture production and potential biotechnological applications. Environ Biol Technol 2:57–71. https://doi.org/10.53623/tebt.v2i2.451

Özkan G, Bilek SE (2014) Microencapsulation of natural food colourants. Int J Nut Food Sci 3:145–156. https://doi.org/10.11648/j.ijnfs.20140303.13

Poling EB (1997) Blackberries. J Small Fruit Vitic 4:33–69. https://doi.org/10.1300/J065v04n01_02

Porto ELN, Lima FF de, Sousa RM, Banhara DG de A, Mendonça WCB, Honorato CA (2020) *Schinus terebinthifolius* raddi pepper oil used as na addictive in *Hyphessobrycon eques* steindachner fish diet. Res Soc Develop 9:e192963118. https://doi.org/10.33448/rsd-v9i6.3118

Rana KJ (1997) Guidelines on the collection of structural aquaculture statistics. Supplement to the programme for the world census of agriculture 2000. FAO 1:1–56

Rashidian G, Rainis S, Prokić MD, Faggio C (2021) Effects of different levels of carotenoids and light sources on swordtail fish (*Xiphophorus helleri*) growth, survival rate and reproductive parameters. Nat Prod Res 35:3675–3686. https://doi.org/10.1080/14786419.2020.1723091

Rekha R, Nimsi KA, Manjusha K, Sirajudheen TK (2024) Marine yeast *Rhodotorula paludigena* VA 242 a pigment enhancing feed additive for the ornamental fish koi carp. Aquac Fish 9:66–70. https://doi.org/10.1016/j.aaf.2022.05.008

Ringø E, Ashour M, Ahmed S, Sharawy Z, Goda A, El-Haroun E (2025) Microalgae and seaweeds as feed additives for aquatic animals: effects on growth, immunity, and disease resistance. In: Algae - Science and Applications. IntechOpen

Rosell M de los Á, Quizhpe J, Ayuso P, Peñalver R, Nieto G (2024) Proximate composition, health benefits, and food applications in bakery products of purple-fleshed sweet potato (*Ipomoea batatas* L.) and its by-products: a comprehensive review. Antioxidants 13:954. https://doi.org/10.3390/antiox13080954

Rotili MCC, Villa F, Silva DF da, Rosanelli S, Braga GC, Ritter G (2022) Bioactive compounds, bromatological and mineral characterization of blackberries in a subtropical region. Revista Ceres 69:13–21. https://doi.org/10.1590/0034-737x202269010003

Sánchez C, Santos M, Vasilenko P (2019) Batata-doce branca, roxa ou alaranjada? avaliação qualitativa e nutricional. Vida Rural

Sathyaruban S, Uluwaduge DI, Yohi S, Kuganathan S (2021) Potential natural carotenoid sources for the colouration of ornamental fish: a review. Aquac Int 29:1507–1528. https://doi.org/10.1007/s10499-021-00689-3

Scárdua MP, Walker SM, Godoy AC, Honorato CA, Neu DH (2024) The role of phenylalanine in the fish pigmentation process: a review. Int Aquat Res 16:101–111. https://doi.org/10.22034/iar.2024.2007852.1607

Sia YJ, Chua LS, Aman Nor NF, Soo J, Sari E (2025) Spray drying and characterisation of anthocyanin rich microcapsules from jaboticaba juice with maltodextrin. Food Biosci 68:106446. https://doi.org/10.1016/j.fbio.2025.106446

Simmonds NW (1993) Sweet potato: an untapped food resource. In: Woolfe JA (ed) Experimental Agriculture, 1st edn. Cambridge University Press , Cambridge, pp 132–132

Singh MK, Borgohain P, Kaur K, Gogoi S (2021) Emergence of plants in fish pigmentation. Agric Res 10:535–542. https://doi.org/10.1007/s40003-021-00551-1

Stoclet JC, Chataigneau T, Ndiaye M, Oak MH, El Bedoui J, Chataigneau M, Schini-Kerth VB (2004) Vascular protection by dietary polyphenols. Eur J Pharmacol 500:299–313. https://doi.org/10.1016/j.ejphar.2004.07.034

Sukardi P, Hana H, Prayogo NA, Sulistyo I, Soedibya PHT, Harisam T, Winanto T (2018) A lipid-walled microcapsule diet as co-feed for early feeding the *Osphronemus gourami* (Lacepede) larvae. Acta Sci 40:38335. https://doi.org/10.4025/actascianimsci.v40i1.38335

Sumana SL, Xue T, Hu H, Abdullateef MM, Shui Y, Ayana GU, Kayiira JC, Zhang C, Samwel BJ, Zhu J, Su S, Ebenezer A, Simbo EBS, Xiaojun J (2025) Medicinal plants as ecological solutions for fish growth and immunostimulatory effects in aquaculture. Aquac Res 2025:. https://doi.org/10.1155/are/9778623

Tang C, Han J, Chen D, Zong S, Liu J, Kan J, Qian C, Jin C (2023) Recent advances on the biological activities of purple sweet potato anthocyanins. Food Biosci 53:102670. https://doi.org/10.1016/j.fbio.2023.102670

Temple E, Langdon C (2009) Delivering oxytetracycline to first-feeding zebrafish, *Danio rerio* (Hamilton) and goby, *Asterropteryx semipunctata* Rüppell, larvae using lipid spray beads. J Fish Dis 32:279–292. https://doi.org/10.1111/j.1365-2761.2008.00992.x

Teow CC, Truong V-D, McFeeters RF, Thompson RL, Pecota KV, Yencho GC (2007) Antioxidant activities, phenolic and β-carotene contents of sweet potato genotypes with varying flesh colours. Food Chem 103:829–838. https://doi.org/10.1016/j.foodchem.2006.09.033

Valenti WC, Barros HP, Moraes-Valenti P, Bueno GW, Cavalli RO (2021) Aquaculture in Brazil: past, present and future. Aquac Rep 19:100611. https://doi.org/10.1016/j.aqrep.2021.100611

Vanegas-Espinoza PE, Pérez-Escalante V, Aguirre-Guzman G, Hoyos-Leyva JD, Del Villar-Martínez AA (2019) Microencapsulation of anthocyanins from roselle (*Hibiscus sabdariffa*) and its application on a pigment supplied diet to fantail goldfish (*Carassius*

auratus). Aquac Int 27:1801–1811. https://doi.org/10.1007/s10499-019-00430-1
Velichkova K, Sirakov I, Stoyanova S, Simitchiev A, Yovchev D, Stamatova-Yovcheva K (2024) Effect of replacing fishmeal with algal meal on growth parameters and meat composition in rainbow trout (*Oncorhynchus mykiss* W.). Fishes 9:249. https://doi.org/10.3390/fishes9070249
Vissio PG, Darias MJ, Di Yorio MP, Pérez Sirkin DI, Delgadin TH (2021) Fish skin pigmentation in aquaculture: the influence of rearing conditions and its neuroendocrine regulation. Gen Comp Endocrinol 301:113662. https://doi.org/10.1016/j.ygcen.2020.113662
Vizzotto M, Pereira MC (2011) Amora-preta (*Rubus* sp.): otimização do processo de extração para determinação de compostos fenólicos antioxidantes. Rev Bras Frutic 33:1209–1214. https://doi.org/10.1590/s0100-29452011000400020
Vizzotto M, Raseira M do CB, Pereira MC, Fetter M da R (2012) Teor de compostos fenólicos e atividade antioxidante em diferentes genótipos de amoreira-preta (*Rubus* sp.). Rev Bras Frutic 34:853–858. https://doi.org/10.1590/S0100-29452012000300027
Wang SY, Jiao H (2000) Scavenging capacity of berry crops on superoxide radicals, hydrogen peroxide, hydroxyl radical's, and singlet oxygen. J Agric Food Chem 48:5677–5684. https://doi.org/10.1021/jf000766i
Wang SY, Maas JL, Payne JA, Galletta GJ (1995) Ellagic acid content in small fruits, mayhaws, and other plants. J Small Fruit Vitic 2:39–49. https://doi.org/10.1300/J065v02n04_03
Wang X, Wan X, Wu J, Cui L, Xiao Q (2024) Comparative study of polysaccharide metabolites in purple, orange, and white *Ipomoea batatas* tubers. Food Chem X 24:101855. https://doi.org/10.1016/j.fochx.2024.101855
Wu R, Frei B, Kennedy JA, Zhao Y (2010) Effects of refrigerated storage and processing technologies on the bioactive compounds and antioxidant capacities of "Marion" and "Evergreen" blackberries. LWT - Food Sci Technol 43:1253–1264. https://doi.org/10.1016/j.lwt.2010.04.002
Wu Y, Zhang C, Huang Z, Lyu L, Li J, Li W, Wu W (2021) The color difference of *Rubus* fruits is closely related to the composition of flavonoids including anthocyanins. LWT 149:111825. https://doi.org/10.1016/j.lwt.2021.111825
Xu J, Su X, Lim S, Griffin J, Carey E, Katz B, Tomich J, Smith JS (2015) Characterisation and stability of anthocyanins in purple-fleshed sweet potato P40. Food Chem 186:90–96. https://doi.org/10.1016/j.foodchem.2014.08.123
Yilmaz E (2019) Effects of dietary anthocyanin on innate immune parameters, gene expression responses, and ammonia resistance of Nile tilapia (*Oreochromis niloticus*). Fish Shellfish Immunol 93:694–701. https://doi.org/10.1016/j.fsi.2019.08.033
Yoshimoto M, Okuno S, Yamaguchi M, Yamakawa O (2001) Antimutagenicity of deacylated anthocyanins in purple-fleshed sweetpotato. Biosci Biotechnol Biochem 65:1652–1655. https://doi.org/10.1271/bbb.65.1652
Yúfera M, Kolkovski S, Fernández-Díaz C, Rinchard J, Lee KJ, Dabrowski K (2003) Delivering bioactive compounds to fish larvae using microencapsulated diets. Aquaculture 227:277–291. https://doi.org/10.1016/S0044-8486(03)00509-X
Zarantoniello M, Cattaneo N, Conti F, Carrino M, Cardinaletti G, Şener İ, Olivotto I (2024) Mitigating dietary microplastic accumulation and oxidative stress response in european seabass (*Dicentrarchus labrax*) juveniles using a natural microencapsulated antioxidant. Antioxidants 13:812. https://doi.org/10.3390/antiox13070812
Zhang Z-F, Fan S-H, Zheng Y-L, Lu J, Wu D-M, Shan Q, Hu B (2009) Purple sweet potato color attenuates oxidative stress and inflammatory response induced by d-galactose in mouse liver. Food Chem Toxicol 47:496–501. https://doi.org/10.1016/j.fct.2008.12.005
Zhao J-G, Yan Q-Q, Lu L-Z, Zhang Y-Q (2013) *In vivo* antioxidant, hypoglycemic, and anti-tumor activities of anthocyanin extracts from purple sweet potato. Nutr Res Pract 7:359–365. https://doi.org/10.4162/nrp.2013.7.5.359
Zhao X, Corrales M, Zhang C, Hu X, Ma Y, Tauscher B (2008) Composition and thermal stability of anthocyanins from chinese purple corn (*Zea mays* L.). J Agric Food Chem 56:10761–10766. https://doi.org/10.1021/jf8025056
Zielinski AAF, Goltz C, Yamato MAC, Ávila S, Hirooka EY, Wosiacki G, Nogueira A, Demiate IM (2015) Blackberry (*Rubus* spp.): influence of ripening and processing on levels of phenolic compounds and antioxidant activity of the 'Brazos' and 'Tupy' varieties grown in Brazil. Ciencia Rural 45:744–749. https://doi.org/10.1590/0103-8478cr20120715

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