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Understanding the Application of Plant Extracts in Wound Healing of Fish: A Comprehensive Review

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Abstract

This review explores the latest developments in the use of plant extracts to promote fish wound healing. Healing from wounds is an essential part of maintaining fish health, especially in aquaculture where injuries can result in large losses. The potential therapeutic benefits of plant extracts, such as their antimicrobial, anti-inflammatory and tissue-regenerating capabilities, have drawn attention. This paper presents an overview of the state of the art in fish wound-healing research, focusing on important plant extracts. It discusses these extracts' mechanisms of action, how well they work to promote wound healing, and what influences how effective they are. The review also examines future directions and possible obstacles in this area, highlighting the necessity of more clinical trials and standardised research methodologies to validate the use of plant extracts for fish wound healing.

1 | Introduction

In fish culture, wounds are commonly treated using antibiotics such as rifampicin and oxytetracycline (Roy et al. 2019; Yun et al. 2021). However, worries have been expressed regarding the possibility of drug-resistant bacteria emerging and drug residue bioaccumulating in fish bodies, which may have an effect on consumers directly or indirectly (Adeshina et al. 2020).

In aquaculture, medicinal herbal extracts are considered a viable substitute for synthetic medications (Gabriel et al. 2019). They exhibit promise as organic health enhancers and antioxidants (Wang et al. 2024). Because of their bioactive components, herbal medicines, also referred to as alternative and complementary medicines, have been used for many years to treat medical conditions and improve wellness. Therapeutic herbal extracts provide advantageous physiologically active metabolites that have several benefits, such as immune system modulation (Zanuzzo et al. 2015; Yang et al. 2015), enhancement of antioxidation, enhanced digestion, growth promotion, antidepressant as well as appetite-stimulating effects (Citarasu 2010; Zahran et al. 2014).

According to Adenıyı et al. (2018), wound healing occurs spontaneously when damaged tissue is replaced and tissue integrity is restored. All living things go through a natural biological process called wound healing, however, certain conditions can interfere with this process or cause it to proceed more slowly (Guo and DiPietro 2010). If pathogenic bacteria are present, the healing process may be impeded and the wound condition may worsen (Hassan et al. 2023). The management and treatment of wounds can greatly benefit from the use of plants and their extracts, which are organic products. The ability of herbal products to heal wounds has been linked to the antimicrobial and antioxidant qualities of phytobiotics (Abdulla et al. 2009; Nazeemashahul et al. 2024). Plant phytochemical components like flavonoids, alkaloids and tannins aid in animals' ability to heal wounds (Rex et al. 2018; Cedillo-Cortezano et al. 2024). Herbal remedies made from the seeds of *Tamarindus indica* (Linn 1753; Adeniyi et al. 2017), the flowers of *Rafflesia hasseltii* (Abdulla et al. 2009), the bulb of *Allium cepa* and the leaves of *Tetracarpidium conophorum* (Bello et al. 2013) have been applied in wound healing of fish. Herbal products with great potential for wound healing have been tested on rats or mice using *Acorus calamus* root and rhizome (Shi et al. 2014) and fish using *Azadirachta indica* leaf and oil (Alam et al. 2014).

It appears little is known about fish wound-healing processes. To this end, this review seeks to provide updated information on the application of plant extracts in wound healing in fish.

2 | Wound-Healing Mechanism in Fish

The healing of wounds in fish is a complicated, multi-phase process that guarantees quick and effective tissue repair to preserve homoeostasis and ward off infection. When pathogens and debris are removed from the wound site, immune cells migrate there and initiate the inflammatory phase. The proliferative phase, which is marked by the growth of new tissue, angiogenesis and re-epithelialisation, the process by which new skin cells cover the wound comes next. Collagen is formed by fibroblasts and is an essential component of the extracellular matrix (ECM) that facilitates the growth of new tissue. In the last stage, known as remodelling, the damaged area's structural integrity and functionality are restored by realigning collagen fibres, strengthening the new tissue and removing extra cells. A complex web of cytokines, growth factors and signalling pathways controls the entire process, ensuring that the healing stages are precisely coordinated and timed. This section discusses the peculiar structure of fish skin and how it relates to the processes involved in wound healing.

2.1 | Anatomy of Fish Skin and Wound-Healing Process

The multipurpose tissue that makes up fish skin carries out numerous vital functions, including hormone metabolism, chemical and physical defence, sensory function and behavioural reasons (Rakers et al. 2010). The skin of fish like all other organisms serve as a protective barrier that separates the body from its surroundings. Moreover, it carries out sensory tasks (Bleckmann and Zelick 2009) and keeps fish from becoming dehydrated (Shephard 1993). To preserve the integrity of the animal, the skin must remain intact (Yun et al. 2021). A thorough understanding of the anatomy of fish skin is essential to understanding the regenerative and repair processes involved in wound healing. Although there are a wide range of fishes, there are some common features in the anatomy of fish skin (Sveen et al. 2020). These common features include the outer cuticle, an outer epithelial layer, the intermediate dermal layer, as well as the deeper hypodermis. In fish, the epidermis, dermis and external mucus layer combine to form the skin.

The outermost layer, known as the epidermis, is primarily made up of club cells, mucus-secreting unicellular glands and epithelial cells known as keratinocytes (Halbgewachs et al. 2009; Päkk et al. 2011). The epidermis of the skin is composed of several cell types called mucous cells, which secrete surface mucus. These cells are known to contain a range of biologically active macromolecules, most notably glycoproteins (Yang et al. 2019). The bulk of the epidermis is composed of keratocyte cells, also known as filament-containing cells or Malpighian cells, and mucous-producing cells (Elliott 2011). According to Esteban (2012), the epidermis plays crucial roles in both skin repair and stable conditions.

Following the epidermis, the dermis is the next inner layer. It is separated from it by an acellular basement membrane and is thicker, vascularised, and divided into two sub-layers: the stratum spongiosum and the stratum compactum (Elliott 2000). Except for a tiny number of mucous cells that secrete mucus, the dermis is completely composed of living cells, unlike mammals (Guardiola et al. 2022).

The stratum laxum, or outer layer, and the stratum compactum, or deeper layer, are the two further divisions of the dermis. There are a variety of cell types and tissues in the stratum laxum. These consist of peripheral nerve cells, chromatophores, iridophores, nerve cells, loose connective tissue and blood vessels (Elliott 2011; Rasmussen et al. 2018). According to Rummer et al. (2014), the blood vessels in the dermal layer are a component of a secondary vascular system. It is believed to be involved in gas transfer, nutrition supply and acid–base regulation (Glover et al. 2013). The primary vasculature gives rise directly to the secondary vascular system (Olson 1996). Blood flow to the secondary system is low in steady state, however, exercise or hypoxia can increase blood flow, as demonstrated by the glass catfish (Rummer et al. 2014).

A connective tissue rich in adipocytes and blood vessels forms the hypodermis. The appropriate vascularisation, pigmentation and mechanical properties of the entire skin are attributed to the latter layer of skin (El Zoghby et al. 2016).

Maintaining bodily integrity and protecting against infections requires the healing of wounds (Flanagan 2013). The natural process of wound healing allows injured tissues to regain their structural and functional integrity. To repair the lesions and return the body to its normal state, it involves a number of cellular and biochemical pathways (Barku 2019). Fish wound healing typically involves several stages, including re-epithelialisation, inflammation, cell proliferation leading to the formation of granulation tissue and tissue remodelling (Richardson et al. 2013). Figure 1 shows the healing processes in fish.

Figure 1 suggests that the wound-healing cascade consists of the wound immediately after re-epithelialisation during a period of inflammation greater than 2 weeks (Sveen et al. 2019). Although the skin pigmentation appears similar to that before the wound, more tissue remodelling and repair may take several months, and when the underlying muscle is damaged, scale regeneration may take more than a year (Virtanen et al. 2023).

Different stages, including platelet accumulation, coagulation and leukocyte migration, are involved in the inflammatory phase (Reza Farahpour 2019). Wound contraction, angiogenesis, fibroplasia and re-epithelialisation are the stages of tissue formation. The dermis may produce collagen and matrix proteins in response

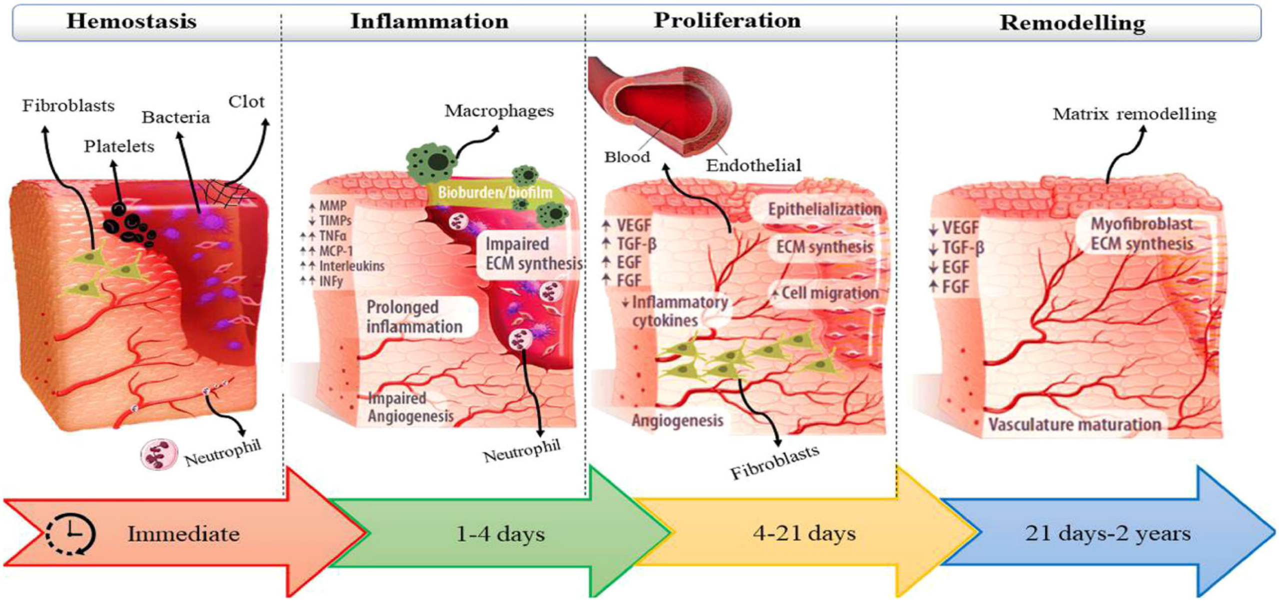

FIGURE 1 | Wound-healing process (adopted from Esmaeili et al. 2023).

to injury during the 1-month remodelling phase before reverting to its pre-injury phenotype (Bainbridge 2013).

2.2 | Cellular Response to Wounding

The healing of fish wounds is a complicated web of biological processes. In this section, the processes involved in the cellular response to wounds are discussed.

2.2.1 | Inflammation

During inflammation in the process of fish wound healing, white blood cells migrate to the wound site, releasing chemical signals that attract other immune cells (Schmidt 2013). Inflammation plays an important role in the process of wound healing in fish, and it involves a complex series of events (Eming et al. 2017). During the process, vasodilation occurs increasing the flow of blood to the wound site resulting in increased oxygen and nutrient delivery (Dalisson and Barralet 2019). White blood cells migrate to the site of the wound, where they phagocytose bacteria and debris (Glenn and Armstrong 2019). Foreign particles and dead tissue are engulfed and destroyed by leukocytes. Moreover, immune cells are activated producing reactive oxygen species (ROS) and nitric oxide (NO) aiding in pathogen elimination (Esteban et al. 2015). Once the fish wound is clean and pathogens are eliminated, the inflammatory response subsides and the wound of the fish enters the proliferative phase of healing (Sveen 2018).

2.2.2 | Debridement

Debridement, which involves clearing the wound site of dead tissue, debris and bacteria, is an essential stage in the healing process of fish wounds (Shalaby et al. 2020). Enzymes and cells break down dead tissue and debris, preparing the wound for repair (Esmaeili et al. 2023). This procedure is crucial because it enhances the migration and proliferation of cells involved in the healing process of fish wounds and prevents infection (Wallner et al. 2022). Mechanical debridement in fish wound healing occurs through water currents, scratching or other mechanical forces removing dead tissue and debris (Sharma et al. 2022). Cellular debridement in fish wound healing occurs when immune-like macrophages and neutrophils phagocytose and remove dead tissue and debris (Wilkinson and Hardman 2020). During enzymatic debridement, fish produce enzymes like proteases, lipases and DNases that break down dead tissue and debris (Duarte et al. 2016).

2.2.3 | Cell Differentiation

Cells specialise into various types (e.g., epithelial, fibroblast, endothelial) to restore tissue function in the process of fish wound healing (Gurevich et al. 2021). Cell differentiation plays a crucial role in the fish wound-healing process as it enables the formation of new tissue to replace damage or lost tissue (Shaw and Martin 2016). As epithelial cells create new layers to cover wounds, undifferentiated cells undergo a transformation into specialised cell types (Santos et al. 2014). The fibroblast produces collagen and the ECM for tissue strength and structure (Subhan et al. 2021). Osteoblasts generate new bone tissues to heal damaged skeletal structures, while endothelial cells form new blood vessels for the supply of oxygen and nutrients (Ramasamy 2017). With myocytes, new muscle tissue is formed to restore functional integrity (Louie et al. 2017).

2.2.4 | Matrix Synthesis

Cells produce ECM components (e.g., collagen, proteoglycans) to rebuild tissue structure (Karamanos et al. 2021). Matrix synthesis is a critical step in fish wound healing, when a new ECM is created to replace damaged tissues (Rousselle and Montmasson 2019). In this process, new collagen fibres are deposited and glycoproteins and proteoglycans are synthesised (Bretaud et al. 2019). Additionally, the hyaluronic acid and other ECM components are produced as a result of this fish wound-healing process (Gomathy et al. 2024). Fish wounds require matrix synthesis to heal because it provides the wound with structural support and strength, promotes cell migration and proliferation, and stimulates tissue remodelling and repair (Esmaeili et al. 2023).

2.2.5 | Angiogenesis

At this stage of cellular response to wound healing, new blood vessels form supplying oxygen and nutrients to the healing tissue of wounded fish (Chen et al. 2021). Before white blood cells and chemical signals are delivered to the wound site, a number of growth factors, including vascular endothelial growth factor (VEGF), fibroblast growth factor (FGF) and platelet-derived growth factors (PDGFs), are released. This promotes angiogenesis (Catanzano et al. 2021). New blood vessels mature forming a tubular structure with the new vessels connecting with existing ones, restoring blood flow to the wound site (Guo et al. 2022). At maturation levels, the new vessels mature becoming stronger and more functional (Schmidt 2013). Angiogenesis in fish wound healing is crucial as the process is rapid and efficient allowing fish to recover quickly from wounds and injuries (Chen et al. 2019).

2.2.6 | Epithelialisation

Epithelial cells migrate and differentiate to restore the outer layer of the fish skin. This crucial process in fish wound healing causes new epithelial layers to form and cover the wound site restoring the integrity of the skin and scales (Costa 2017).

White blood cells and chemical signals clear the fish wound of debris and bacteria at this stage. As a result, the surrounding tissues' epithelial cells become stimulated, multiply and migrate to the wound site (Sveen et al. 2021). The epithelial tongue extends over the wound of the fish covering it (Richardson et al. 2016). The cells of the epithelial cell differentiate into specific cell types such as mucous cells, keratinocytes and melanocytes maturing to form the functional epithelial layer (Akat et al. 2022). Moreover, in fish, new scales regenerate from the epithelial layer restoring the natural armour and protective barrier (White 2018). The fish's scales and skin integrity are restored when the epithelial layer seals the wound (Costa and Power 2018).

2.2.7 | Fibroplasia

Fibroblasts play a role in the cellular response to wound healing in fish (Kalaiselvi et al. 2019). They create collagen to fortify the incision, especially during the phases of fish wound healing that include rebuilding and repair (Oslan et al. 2022). Fibroblasts move to the wound site during the healing process in fish, multiply and proliferate, increasing their numbers to support the healing process (Chen et al. 2019). Fibroblasts create and secrete collagen during the fish-healing process, which is an essential part of the ECM that gives the wound strength and structural support (Sharma et al. 2022). The fibroblasts contract pulling the wound edges together and facilitating tissue closure (Richardson et al. 2016). In the end the fibroblasts continue to produce and organise ECM components, remodelling the tissue to restore its original strength and function (Keane et al. 2018).

2.2.8 | Remodelling

Remodelling forms a crucial stage in the cellular response to fish wound healing (Gómez et al. 2020). At this stage, the newly formed tissue is reorganised and refined, restoring function and appearance (Tiwari et al. 2023). During this stage, newly formed tissue is reorganised and restored to its original function and structure (Rousselle and Montmasson 2019). Collagen fibres are reorganised and realigned to restore tissue strength and elasticity (Murcia 2017). The ECM is refined with excess components removed and new ones deposited (Tzadik et al. 2017). Depending on the extent and size of the wound, the fish's general health and the surrounding circumstances, the remodelling stage of fish wound healing can take several weeks to months to finish (Sveen et al. 2020).

2.2.9 | Immunomodulation

At this stage in the cellular response to fish wound healing, the immune system regulates the healing process, preventing infection and promoting repair (Gómez et al. 2020). At this stage in fish, the immune system is activated to fight infection, but excessive inflammation can hinder healing. Immunomodulation helps regulate inflammation preventing tissue damage (Mokhtar et al. 2023). Additionally, the balance of pro- and anti-inflammatory cytokines aids in the healing of fish wounds (Chen et al. 2020). Pro-inflammatory cytokines reduce tissue damage (Zheng et al. 2017). In fish, immunomodulation controls the activation, growth and differentiation of immune cells like neutrophils, lymphocytes and macrophages (Ching et al. 2021). Immunomodulation also promotes tissue repair by regulating growth factors, ECM deposition and angiogenesis (Julier et al. 2017).

2.2.10 | Cytokine Signalling

At this stage in the cellular response to fish wound healing, chemical signals coordinate cellular responses, directing the healing process (Sveen et al. 2020). During this stage of wound healing in fish, cytokine signalling plays a role communicating between cells and orchestrating the immune response (Leiba et al. 2023). Cytokines are released in response to wound-induced stress signals, such as damage-associated molecular patterns (DAMPs; Schmidt 2013). Pro-inflammatory cytokines are produced when immune cells are drawn to the wound site and inflammation is encouraged (Chen et al. 2020). Fish wound healing is facilitated by cytokines such as epidermal growth factor (EGF) and FGF, which encourage cell proliferation and differentiation and support tissue regeneration (Chen et al. 2019).

2.2.11 | Growth Factor Regulation

Proteins promote the migration, differentiation and development of cells. Together, these biological mechanisms help fish wounds heal and regain tissue integrity (Sveen et al. 2020). Growth factors like EGF, FGF, VEGF and PDGF are released from wounded tissue, platelets and macrophages (Vaidyanathan 2021). By binding to particular receptors on the surface of target cells, these growth factors initiate intracellular signalling pathways (Gilbert et al. 2016). Growth factors help tissue regeneration and repair by stimulating cell migration and proliferation. Certain growth factors, such as FGF and EGF, also encourage cell differentiation (Farooq et al. 2021). As a result of growth factors like PDGF and VEGF promoting angiogenesis, new blood vessels are formed to supply the wound (Elbialy et al. 2020).

2.3 | Growth Factors in Wound Healing

Growth factors are essential for the healing of fish wounds. Growth factors have the potential to expedite the healing process through various mechanisms. Growth factors, first of all, have chemotactic qualities that attract inflammatory and fibroblast cells to the wound. Second, growth factors function as mitogens, encouraging the growth of cells. In this section, different growth factors and their roles in wound healing are discussed.

2.3.1 | Platelet-Derived Growth Factor

Initiating the inflammatory process stage, PDGF stimulates the mitogenicity and chemotaxis of cells, including neutrophils, macrophages, fibroblasts and smooth muscle cells, to the wound site (Gonzalez et al. 2016). When fish PDFG attaches to particular receptors on target cells' surfaces, intracellular signalling pathways are triggered (Islam et al. 2016). It increases cell survival, proliferation and migration by activating the MAPK/ERK and PI3K/Akt signalling pathways (Wen et al. 2022). Genes such as fibronectin and collagen that are involved in tissue regeneration and repair are stimulated to express themselves by PDGF (Horikawa et al. 2015). It modulates the immune response reducing inflammation and promoting a conducive environment for wound healing (Larouche et al. 2018). PDGF in fish has been shown to enhance wound closure and tissue regeneration, promoting scale regeneration and fin repair, supporting immune modulation and reducing inflammation (Gomathy et al. 2024).

2.3.2 | Vascular Endothelial Growth Factor

In addition to influencing wound healing and closure and the formation of granulation tissue, VEGF stimulates the formation of new blood vessels as well as tissue proliferation, differentiation, migration, as well as survival, all of which contribute to the angiogenesis process (Honnegowda et al. 2015). VEGF is released from wounded tissue and macrophages in response to hypoxia and stress signals in fish (Zhao et al. 2022). It encourages angiogenesis, the formation of new blood vessels that bring nutrients and oxygen to the wound (Johnson and Wilgus 2014). VEGF promotes endothelial cell migration and proliferation, which results in the development of new vessel sprouts (Vandekeere et al. 2015). VEGF promotes the expression of angiogenesis-related genes, including vascular endothelial-cadherin and Endothelial nitric oxide synthase (Melincovici et al. 2018).

2.3.3 | Epidermal Growth Factor

In addition to promoting the growth and differentiation of fibroblasts, endothelial cells and epithelial cells, EGF also exhibits mitogenic and migratory activity on the keratinocytes that border the lesions (Peplow and Chatterjee 2013). It has the ability to promote the expression of genes involved in cell proliferation and differentiation, such as cyclin D1 and keratin 18, EGF is crucial for wound healing (Wang et al. 2018).

2.3.4 | Fibroblast Growth Factor

FGFs are important players in the process of wound healing (Farooq et al. 2021). Smooth muscle cells, endothelial cells, fibroblasts, keratinocytes, chondrocytes and mast cells all secrete FGFs (Riswana and Don 2019). There has been evidence of an increase in FGF-2 production during the acute cutaneous wound process, and this protein is in charge of granulation tissue formation, re-epithelialisation and tissue remodelling (Cañedo-Dorantes and Cañedo-Ayala 2019).

2.4 | Extracellular Matrix Remodelling

The ECM is remodelled during the wound-healing process in fish through the action of enzymes called matrix metalloproteinases (MMPs), which break down the ECM and allow for the migration of cells and the formation of new tissue (Xue and Jackson 2015). The ECM is composed of various proteins and molecules that provide structure and support to the tissue, and its remodelling is a crucial step in the wound-healing process (Solarte et al. 2022).

2.5 | Inflammatory Response in Fish Wound Healing

Inflammation plays an important role in fish wound healing, and it involves various immune cells and cytokines (Campos-Sánchez and Esteban 2021). Inflammation aids in preventing additional harm and infection to the wound (Antonio et al. 2015). Moreover, inflammation aids in removing dead tissue and debris from the wound and plays a big role in repair where it promotes tissue repair and regeneration (Oishi and Manabe 2018).

Immune cells are involved in fish wound healing, of such are neutrophils, which are the first responders to the wound, producing cytokines such as tumour necrosis factor-alpha (TNF-α) and interleukin-1 beta (IL-1β; Chen et al. 2020). Another kind of immune cell that is essential to phagocytosis is the macrophage, which generates cytokines such as interleukin-6 (IL-6) and interleukin-12 (IL-12; Arango Duque and Descoteaux 2014). T-cells are also involved in cell-mediated immunity, producing cytokines like IFN-γ (Broere and van Eden 2019). B-cells, a type of immune cell, were found to produce antibodies to fight infection during the process (Hoffman et al. 2016).

Fish wounds produce TNF-α, a cytokine that promotes inflammation and attracts immune cells to the site of injury (Zou and Secombes 2016). Furthermore, IL-1β stimulates the healing process, increases inflammation and triggers the production of other cytokines (Campos-Sánchez et al. 2021). The acute phase response is mediated by the production of IL-6, which causes inflammation and acute phase protein synthesis (Wang et al. 2020). Anti-inflammatory cytokines produced like interleukin-10 (IL-10) reduce inflammation, promote tissue repair and regulate the immune response and transforming growth factor-beta (TGF-β) which promotes tissue repair, regeneration and remodelling, while reducing inflammation (Steen et al. 2020). Together, these immune cells and cytokines facilitate fish wound healing, with inflammation being essential to the early phases of the healing process (Ceballos-Francisco et al. 2017).

2.6 | Effects of Environmental Factors on Fish Wound Healing

Fish wound healing is greatly influenced by environmental factors, which also have a direct impact on the rate and quality of tissue repair. The ideal temperature of the water is crucial because it boosts immunological response and metabolic activity, which speeds up the healing process. On the other hand, high or low temperatures can cause stress and hinder the healing process. Wound healing is greatly impacted by water quality, which includes elements like pH, dissolved oxygen content, and the presence of contaminants. Poor water quality can result in infections and protracted inflammation. Salinity levels have an impact on osmoregulation and general physiological stability, which in turn affects wound healing. Furthermore, a high concentration of microorganisms and pathogens in the water can exacerbate the healing process by raising the risk of secondary infections. As a result, keeping the environment conducive is essential to encouraging fish to heal wounds effectively. In this section, we discuss in detail the effects of environmental factors on fish wound healing.

2.6.1 | Temperature

Temperature affects the wound-healing rate in fish, with optimal temperatures varying by species (Sadat et al. 2022). Research has shown that wound-healing rates in fish are influenced by the temperature of their environment (Jensen et al. 2015). Specifically, with optimal temperatures, which vary by species, fish wound healing occurs faster (Somero 2020). For example, some species like zebrafish and goldfish have optimal wound-healing temperatures between 25 and 30°C (77–86°F), while others like salmon and trout have optimal temperatures between 10 and 15°C (50–59°F; Schmidt 2013). Moreover, fish wound recovery might be hampered by excessively high or low temperatures. While low temperatures can slow down metabolic processes and lower the activity of enzymes involved in wound healing, high temperatures can exacerbate metabolic stress (Chowdhury and Saikia 2020). Fluctuations in temperature can also impact wound healing, as fish may need to divert energy from the healing process to adapt to changing temperatures (Logan and Buckley 2015). It is noteworthy that the ideal temperature needs for wound healing in fish might differ based on their size, species and other environmental conditions. It is essential to provide fish with a steady and species-appropriate temperature range in order to encourage proper wound healing (Nirmal et al. 2022).

2.6.2 | Water Quality

Poor water quality can impede wound healing in fish, while clean water with appropriate pH, ammonia and nitrite levels supports the healing process, making water quality have a significant impact on wound healing in fish (Yavuzcan Yildiz et al. 2017). Poor water quality can impede wound healing in fish, while good water quality can support the healing process (Heath 2018). A stable pH range suitable for the species is essential for proper wound healing (Martins et al. 2023). Moreover, elevated levels of these ammonia and nitrite levels in water quality can hinder wound healing in fish (Ciji and Akhtar 2020). High levels of harmful bacteria in the water can infect the wound and slow healing (Sveen et al. 2020). Furthermore, because both oxygenation and temperature have an impact on the rate at which fish heal wounds, proper conditions are essential for fish wound healing (Abdel-Tawwab et al. 2019). Suitable water hardness is important for wound healing, as it affects the fish's overall health. The availability of nutrients at some levels supports wound healing in fish (Menon et al. 2023). The presence of chemical pollutants can impede wound healing in fish as they interfere with natural repair mechanisms (Authman et al. 2015). The presence of pollutants could also lead to inflammation which could cause tissue damage and delayed healing (Javed and Usmani 2019). Maintaining good water quality by monitoring and controlling these factors can help optimise wound healing in fish (Encinas et al. 2017).

2.6.3 | Microbiota

The microbiota in fish skin and water affect how quickly wounds heal, with some bacteria helping the healing process while others do the opposite (Sehnal et al. 2021). Microbiota play a crucial role in fish wound healing and can influence the healing of wounds in fish (Chen et al. 2020). Beneficial microbiota can produce antimicrobial peptides and compounds that help combat pathogens and prevent infection (Naiel et al. 2023). Fish immune systems and microbiota can interact to modify the immune response, resulting in a balanced immune response and controlled inflammatory response (Firmino et al. 2021). Certain microbiota can generate growth factors to support tissue repair by promoting cell migration, differentiation and proliferation (Farooq et al. 2021). Microbiota can degrade organic matter, removing debris and promoting a clean wound environment which promotes wound healing in fish (Nag et al. 2022). Beneficial microbiota can also outcompete pathogens for resources and space, lowering the risk of infection and accelerating fish wound healing (Ferreira et al. 2022). Microbiota can produce extracellular polymeric substances (EPSs), which can act as a protective barrier, preventing pathogen adhesion and promoting wound healing (Watters et al. 2016).

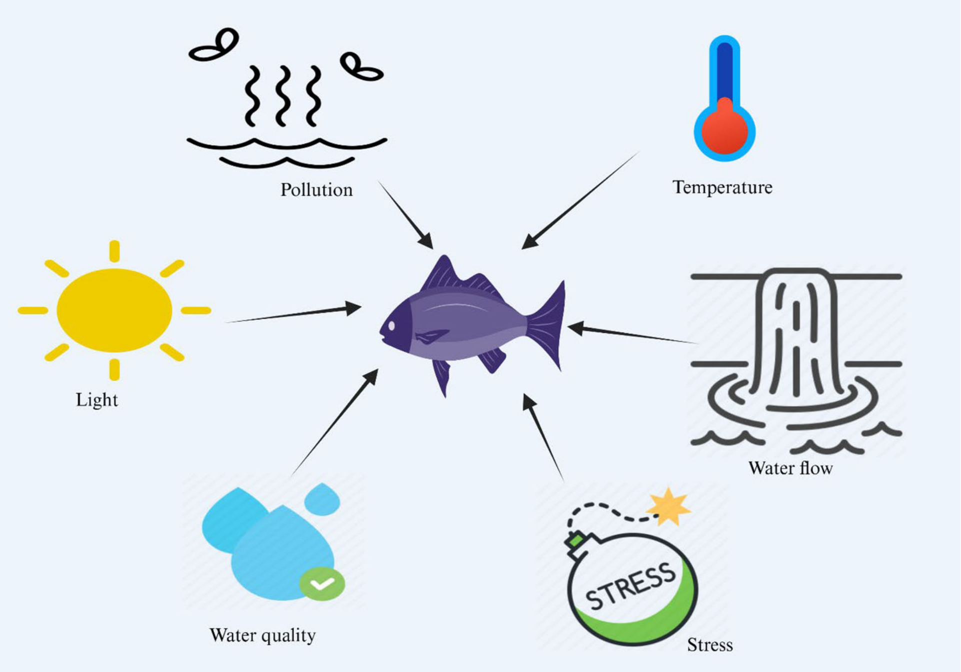

FIGURE 2 | Environmental factors of wound healing in fish.

2.6.4 | Stress

Chronic stress can weaken the immune system and impair wound healing in fish (Sveen et al. 2018). Stress can suppress immune system function in fish and increase cortisol levels, which can impede the healing of wounds in fish (Mateus et al. 2017). Stress can also decrease antioxidant defences, making fish more susceptible to oxidative stress (Hoseinifar et al. 2020). Stress could also increase energy allocation to the stress response, diverting resources from healing (Birnie-Gauvin et al. 2017). Moreover, stress can potentially lead to behavioural changes, such as reduced feeding or increased hiding, which can impede healing (Arechavala-Lopez et al. 2022).

2.6.5 | Water Flow

Adequate water flow and oxygenation promote wound healing by reducing bacterial growth and supporting tissue repair (Sveen et al. 2020; Figure 2). Water flow can impact fish wound healing (Ang et al. 2021). Adequate water flow helps remove bacteria and other microorganisms from the wound, reducing the risk of infection (Ina-Salwany et al. 2019). Additionally, water flow ensures oxygen is delivered to the wound, promoting healthy tissue repair and the healing process of fish wounds (Yoon et al. 2022). Water flow helps remove waste products and debris from the wound, preventing accumulation and promoting a clean environment (Bregnballe 2022). Fish wound healing depends on proper water temperature regulation, which can be achieved through water flow as fish under gentle water flow are less stressed and can heal in a more wholesome environment (Jensen et al. 2015). Water flow ensures nutrients and essential compounds reach the wound, supporting the healing process in fish wound healing (Sharma et al. 2022). Water flow can help remove inflammatory mediators, promoting a balanced inflammatory response aiding in the fish wound-healing process (Mathew-Steiner et al. 2021). Various factors, such as the type of fish and the size of the wound, can affect the ideal water flow. For fish wound healing, a mild to moderate water flow (5–20 cm/s) is generally thought to be advantageous (Thorstad et al. 2012).

2.6.6 | Light

Appropriate light exposure can influence wound healing, with some studies suggesting beneficial effects of specific light spectra on fish wound healing (Hamblin et al. 2019). Light can impact fish wound healing in several ways like photobiomodulation, where specific wavelengths of light (e.g., blue, red or infrared) can stimulate cellular processes, enhancing wound healing in fish (Lee et al. 2023). Circadian rhythm regulation occurs where light–dark cycles can influence the fish's natural circadian rhythm, which can impact hormone regulation, immune response and healing (Solberg 2022). Moreover, vitamin D production is influenced by light which is essential for calcium absorption, immune function and wound healing of fish (Shao et al. 2022). Gentle lighting can reduce stress, promoting a healthy environment for the healing of wounds in fish. Specific wavelengths of light (e.g., ultraviolet) can inhibit bacterial growth, reducing the risk of infection (Fiorito et al. 2015). Light can support photosynthetic processes, maintaining good water quality and reducing the risk of waterborne pathogens that would affect the wound or slow the process of healing in fishes (Svobodova et al. 2017). The specific effects of light on fish wound healing can vary depending on factors like light intensity, wavelength and duration, as well as the fish species and wound type (Kim et al. 2016).

2.6.7 | Social Interaction

Social isolation can stress fish and impede wound healing, while appropriate social interaction can support healing (Guo and DiPietro 2010). Social interaction has a wide range of impacts on fish wound healing, depending on the intensity and nature of the interaction (Agostinho et al. 2016). Gentle social interaction can reduce stress levels, promoting a healthy environment for healing (White et al. 2017). Social interaction can lead to improved water quality, as fish are more likely to swim and explore, promoting water circulation which helps to improve fish wound healing (Martins et al. 2012). Additionally, aggressive or intense social interaction can increase stress levels, impeding healing. Aggressive social interaction can cause fish to rub against each other, potentially reopening wounds (Noble et al. 2012). Social interaction can increase the risk of infection, as fish may come into contact with harmful bacteria or parasites (Chapman et al. 2021).

2.6.8 | Substrate

The type of substrate can affect fish wound healing, with some studies suggesting benefits from specific substrates or enrichment (Vanderzwalmen et al. 2022). Substrates can affect fish wound healing in several ways as a comfortable substrate can reduce stress and promote healing (Näslund and Johnsson 2016). Sharp or abrasive substrates can irritate the wound, delaying healing in fish (Koike 2013). Some substrates (e.g., plants) can conceal the wound, and also support the growth of beneficial bacteria reducing stress and promoting fish wound healing (Näslund and Johnsson 2016). The nature of some substrates like sharp substrates can cause further tissue damage, impeding healing of the fish wound (Sveen et al. 2020). Moreover, substrate can affect water circulation, impacting healing as some substrates (e.g., crushed coral) can help stabilise pH, promoting the healing of fish wounds (Arechavala-Lopez et al. 2022). The presence of some plants can affect nutrient availability, impacting healing for fishes (Yavuzcan Yildiz et al. 2017).

2.6.9 | Pollution

Exposure to pollutants like heavy metals or pesticides can impede wound healing in fish (Chakraborty 2023; Figure 2). Pollution can significantly impact fish wound healing as pollutants can slow down the healing process, allowing wounds to persist and increasing the risk of infection (Authman et al. 2015). Pollutants can weaken fish immune systems, leaving them more susceptible to infection and delaying healing, as well as directly harming tissue, making wounds more serious and difficult to heal (Elgendy et al. 2023). Pollutants can change water chemistry, affecting pH, temperature and other parameters that can help to heal fish wounds (Heath 2018). Moreover, pollutants also foster harmful bacterial growth, leading to infection and impeding fish wound healing as they can disrupt cellular function, making it harder for wounds to heal (Elgendy et al. 2023). Due to their potential to induce chronic inflammation, pollutants can decrease the availability of nutrients, which hinders the fish's ability to heal from wounds (Tungadi 2019).

2.7 | Role of Nutrients and Diet in Fish Wound Healing

Fish wound healing is greatly influenced by diet because it supplies the energy, nutrients and building blocks needed for tissue regeneration and repair (Oliva-Teles 2012). A well-prepared diet can support optimal wound healing in fish, while a diet deficient in essential nutrients can impede the healing process (Oliva-Teles 2012). Diet provides the essential nutrients like protein, vitamins and minerals necessary for tissue repair and regeneration (Ayisi et al. 2018). Proteins are essential for collagen synthesis, cell growth and tissue repair in fish (Subhan et al. 2021). Vitamins are important for collagen production, wound contraction and immune function and antioxidant properties help protect against oxidative stress and tissue damage in fish species (Gasco et al. 2018). Iron is necessary for oxygen transport, energy production and collagen synthesis, with calcium essential for scale regeneration, wound contraction and tissue repair (Costa 2017). Enhanced nutrition for fish promotes and supports immune function, helping to combat infection and promote healing in injured fish (Esteban 2012). Quality diets for a fish diet supports gut health, which is essential for immune function and overall health which helps fight infections and enhance wound healing (Dawood et al. 2018). Furthermore, a fish's ability to produce hormones, which are involved in tissue repair and wound healing, can be influenced by its diet (Lall and Kaushik 2021). Fish diet can affect water quality, which in turn affects wound healing (e.g., high ammonia levels can impede healing; Berzi-Nagy et al. 2021). A diet rich in essential nutrients, antioxidants and anti-inflammatory compounds can support optimal wound healing in fish, while a diet deficient in these nutrients can lead to impaired healing and increased susceptibility to disease (Mu et al. 2018). Fish wound healing is greatly influenced by nutrition and diet because these elements supply the building blocks needed for tissue regeneration and repair (Oliva-Teles 2012).

3 | Mechanisms of Action of Plant Extracts

3.1 | Antimicrobial Properties

Plant extracts have been shown to exhibit antimicrobial properties which can help prevent infection and promote a healthy environment for fish wound healing. The most researched bioactivity with potential use in aquaculture systems is the antibacterial properties of plant products. According to Castro et al. (2008), 31 methanolic extracts of Brazilian plants demonstrated antibacterial activity (agar diffusion assay) against *Aeromonas hydrophila*, *Flavobacterium columnare* and *Streptococcus agalactiae*, fish pathogenic bacteria *F. columnare* was the most susceptible microorganism to the majority of the tested extracts.

According to certain recent studies (Alghazeer et al. 2013; Mendes et al. 2013; Al-Saif et al. 2014), algae and seaweed may be a potential source of antimicrobial products. Previous studies (Dubber and Harder 2008) demonstrated that oarweed (*Laminaria digitata*) hexane extracts (31 mg dry weight/mL) and red hornweed (*Ceramium rubrum*) methanol extracts (10 mg dry weight/mL) elicited potent antibacterial activities against 16 different tested bacteria (fish pathogenic bacteria and marine bacteria). Additionally, they demonstrated that, in general, Gram-positive marine *Bacillaceae* were more vulnerable than Gram-negative marine Vibrionaceae. In a different investigation, the ethanol extract of limu kohu (*Asparagopsis taxiformis*) algae (100 mg/mL) demonstrated broad antibacterial activity (agar diffusion assay) against nine fish pathogenic bacteria, with particular potency against *Vibrio alginolyticus* (17.0 ± 1.4 mm), *Vibrio vulnificus* (16.8 ± 1.0 mm) and *Aeromonas salmonicida* subsp. *salmonicida* (15.0 ± 0.9 mm; Genovese et al. 2012).

3.2 | Appetite Stimulators and Growth Promoters

Several studies have reported enhanced growth and appetite stimulation in cultured fish-fed plant extracts (Harikrishnan et al. 2012; Pavaraj et al. 2011; Takaoka et al. 2011; Table 1). Researchers (Shalaby et al. 2006) demonstrated that adding garlic to the diet increased the food intake, specific growth rate and final weight of Nile tilapia (*Oreochromis niloticus*). A different study found that grouper, *Ephinephelus tauvina*, fed a diet supplemented with a combination of methanolic herb extracts, including ginger (*Zingiber officinalis*), coat buttons (*Tridax procumbens*), long pepper (*Piper longum*), stonebreaker (*Phyllanthus niruri*) and Bermuda grass (*Cynodon dactylon*), showed a 41% increase in weight compared to fish fed the control (Punitha et al. 2008). Researchers (Ji et al. 2007) demonstrated that olive flounder (*Paralichthys olivaceus*) fed a herbal mixture of *Cnidium officiale* (2:2:1:1), hawthorne (*Crataegi fructus*), virgate wormwood (*Artemisia capillaris*) and medicated leaven (*Massa medicata fermentata*) showed higher weight gain than the control fish and a lower content of saturated fatty acids in the carcass and a higher content of unsaturated fatty acids overall. The authors hypothesised that the herbal mixture diets may be the cause of this, with lower plasma triglyceride and higher plasma high-density lipoprotein cholesterol (HDL-CHO) levels. Additionally, it has been demonstrated that plant extracts increase nutrient availability and digestibility, which raises feed conversion and increases protein synthesis (Citarasu 2010; Nya and Austin 2009; Talpur et al. 2013).

These findings also highlight the significance of the appropriate dosage for the intended outcomes and, consequently, the necessity of additional research to chemically characterise extracts in order to measure active molecules and determine sufficient dosages.

3.3 | Plant Extracts as Immunostimulants

Innate (non-specific) and adaptive (specific) immune systems are the two types of the immune system. The primary barrier against invasive pathogens is the innate immune system, which is primarily composed of granulocytes, macrophages, monocytes and humoral elements such as complement systems or lysozymes (Harikrishnan et al. 2009). According to Biobaku and Amid (2018), an immunostimulant is a chemical that strengthens an animal's defence mechanisms or immune response, both specific and non-specific, making it more resilient to illnesses and outside threats. Over the past 10 years, there has been a rise in interest

TABLE 1 | Plant extracts' growth-promoting and immune-stimulating effects on fish.

Plant	Fish	Type of extract	Type of administration	Duration of treatment	Growth promoter/immunostimulant	References
Allium sativum	*Tilapia zilii*	Powder (bulb)	Oral	75	Growth promoter	Jegede (2012)
Cynodon dactylon	*Oncorhyncus mykiss*	Powder	Oral	40	Growth promoter	Oskoii et al. (2012)
Satureja khuzestanica	*Cyprinus carpiio*		Oral	35	Immunostimulant	Khansari et al. (2013)
Sauropus androgynus	*Epinephelus coioides*	Ethanol (leaves)	Oral	70	Immunostimulant	Samad et al. (2014)
Urtica dioica	*Oncorhyncus mykiss*	Water (leaves)	Oral	21	Growth promoter	Dügenci et al. (2003)
Viscum album	*Oncorhynchus mykiss*	Water (leaves)	Oral	21	Growth promoter	Harikrishnan et al. (2009)

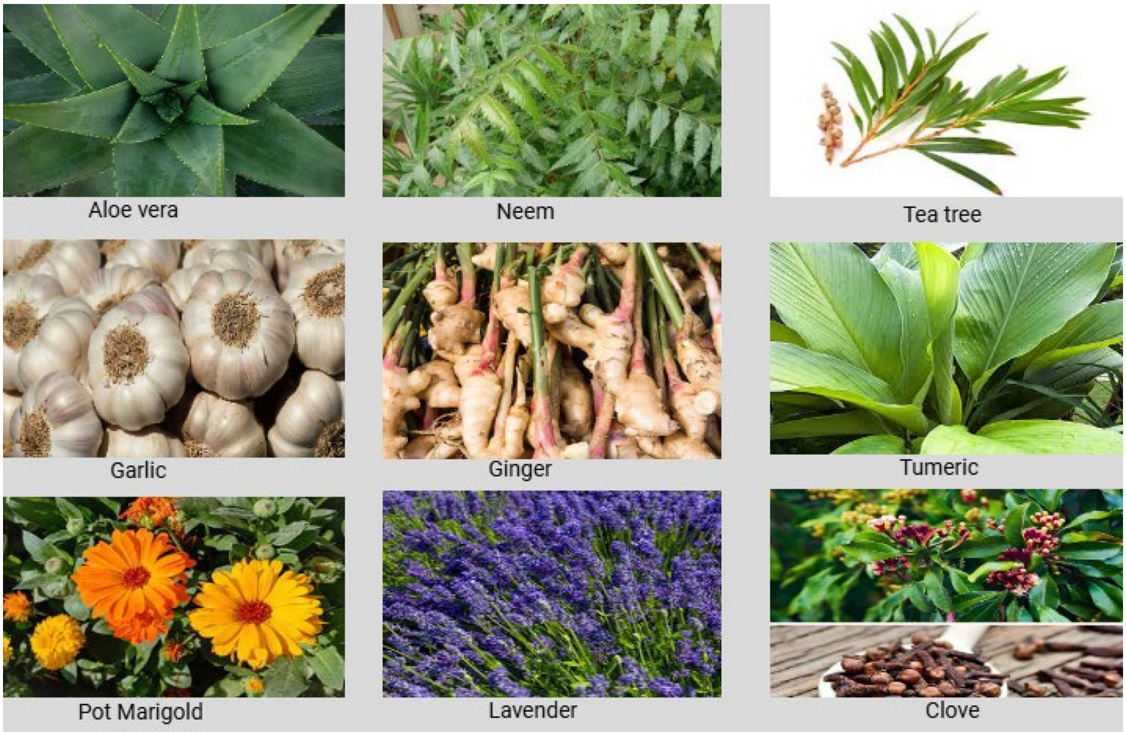

FIGURE 3 | Various common plants used in fish wound healing.

in the application of plant extracts as fish immunostimulants (Galina et al. 2009; Vaseeharan and Thaya 2014). Numerous investigations have tracked the immunological parameters following intraperitoneal injections or oral administrations of plant extracts on various fish species. The results have shown that fish treated with these agents exhibit elevated levels of respiratory burst activity, lysozyme activity, phagocytic activity, complement activity and plasma protein (globulin and albumin; Dügenci et al. 2003; Wu et al. 2010; Table 1). Fish defence is significantly aided by lysozymes, which stimulate antibacterial activity when a complement is present (Harikrishnan et al. 2012). One of the primary mediators of innate immunity to pathogens is phagocytosis, and respiratory burst is an essential effector mechanism for preventing fish pathogen growth (Divyagnaneswari et al. 2007). An increase in fish albumin, globulin and plasma protein is thought to be a powerful innate response (Mirghaed et al. 2023). Other research examined haematological parameters, which give an indication of the health status of fish (Fazio 2019). They discovered that fish treated with plant extracts had significantly higher levels of erythrocytes, lymphocytes, monocytes, haemoglobin and haematocrit than control fish (Yousefi et al. 2021).

4 | Plants Commonly Used in Wound Healing in Fish

The effectiveness of medicinal plants in accelerating fish wound healing is becoming more widely acknowledged, these plants provide a cheap, natural substitute for synthetic treatments. This section delves into some plants commonly used in the wound healing of fish (Figure 3).

4.1 | Aloe Vera

Aloe vera belongs to the Lilaceae family, also referred to as *Aloe barbadensis* (Albahri et al. 2023). Additionally, glycoprotein and mannose-6-phosphate are found in aloe vera (Hossain et al. 2023). It contains alkaloids, flavonoids, tannins, triterpenes, sterols, oses, mucilages and holosides (Benzidia et al. 2019). It also contains barbaloin and polysaccharides (Sánchez-Machado et al. 2017). With the identification of more than 75 physiologically active compounds, aloe vera provides an extensive array of advantages and uses (Choi and Chung 2003). Aloe vera has properties that include immune modulation, antibacterial, anti-inflammatory, antiviral, antidiabetic and antifungal (Djeraba and Quere 2000). Aloe vera has abundant levels of lowering chemical metabolites (Wellia et al. 2024). Additionally, Aloe species are widely recognised for their ability to heal wounds (Zanuzzo et al. 2015).

4.2 | Tea Tree

Melaleuca alternifolia, a tall shrub or tree belonging to the myrtle family (Myrtaceae), is referred to as the tea tree (Bar 2021). It is frequently the dominant species in these environments, growing alongside streams and in marshy areas. The tea tree has a papery, pale bark and a bushy crown. It grows to a maximum height of 7 m. The leaves are grouped in pairs, sometimes in a whorled or scattered pattern. The leaves are 10–35 mm long and 1 mm wide, with a smooth, soft shape. They are rich in oil because they have noticeable glands. Flowers appear as 3–5 cm long spike masses that are white or cream in colour over a brief period of time, primarily from spring to early summer. The 2–3 mm diameter, woody, cup-shaped fruits are strewn throughout the branches

(Puvača et al. 2018). The manufacturing of pharmaceuticals and agriculture both frequently use the natural materials from tea trees. The United States, Japan and Europe have all shown a growing interest in biologically active plant materials in recent years (Puvača et al. 2018). The unique qualities of the myrtle family are helpful in the distillation of essential oils. Tea tree has been utilised in Australia for almost a century as a substitute medicinal plant and as a primary species for commercial productions of essential oils (Carson et al. 2006). Due to its unique antimicrobial properties, tea tree essential oil is frequently applied topically as an antiseptic and antibacterial, it also lowers inflammation and might be useful in treating fungal infections (Hammer et al. 2006). Aromatic liquids known as essential or volatile oils are obtained through distillation from various plant parts, including buds, seeds, leaves, twigs, bark, wood, fruits and roots (Franz and Novak 2020).

4.3 | Neem

Neem (*Azadirachta indica*) is a well-known medicinal plant, having a wide spectrum of biological activity as a traditional medicine for household remedies against various human ailments in ayurveda and homoeopathic medicine (Eid et al. 2017). Recent studies and research show that neem contains many therapeutic effects such as anti-inflammatory, antidiabetic, antifungal, antiviral, antibacterial and antimalarial (Rahmani et al. 2018). Neem contains many active ingredients such as nimbidin, nimbin and nimbidol with anti-inflammatory, antibacterial, antifungal and antiviral properties that may help it accelerate the wound-healing process (Gupta et al. 2019). In addition, neem contains an excellent amount of amino acids, vitamins and minerals that are very important in wound-healing processes in the proliferation phase (Chundran et al. 2015).

4.4 | Turmeric

Bioactive components found in turmeric include flavonoids, β-carotene, phenolic compounds and vitamins C and E. Roughly 0.3%–5.4% of raw turmeric is curcumin, the most researched active ingredient (Akram et al. 2010). Due to its culinary, cosmetic and medicinal qualities, turmeric is the most widely used herb in the world (Pal et al. 2020). In both human and animal models, the medicinal herb turmeric (*Curcuma longa* L.), a member of the Zingiberaceae family, has demonstrated antioxidant, anti-inflammatory and antiviral properties (Bhowmilk et al. 2009; Mishra et al. 2011).

4.5 | Garlic

Garlic, which belongs to the Liliaceae family, is a squamous bulb which has practically been used as traditional medicine for more than 400 years (Gabriel et al. 2019; Shouk et al. 2014). *Allium sativum*, the scientific name for garlic, is recognised for its numerous bioactive constituents, including allicin and alliin, which have a variety of biological effects, including growth promotion, antiviral, antimicrobial and antifungal effects (Aly et al. 2025).

4.6 | Ginger

The rhizomes of the spicy, aromatic ginger plant are frequently used as a functional and medicinal food (Zahid et al. 2021; Ng et al. 2023). Ginger and its constituents have antioxidant activity, which guarantees that macromolecules are shielded from damage caused by free radicals and oxidative stress (Nwosu et al. 2022). Ginger is known for its anti-inflammatory, antibacterial, antioxidant, antipyretic, hepatoprotective, antidiabetic, anticarcinogenic and renal properties (Karuppiah and Rajaram 2012; Kumara et al. 2017).

4.7 | Pot Marigold

Pot marigold is one of the herbal immunostimulants. The industrial plant *Calendula officinalis*, or pot marigold, is a member of the Asteraceae family. This species is abundant in bioactive substances, including polyphenols, terpenoids, saponins, carotenoids, flavonoids, mucilages and steroids. It is found in tropical and subtropical regions of the world (Akbar Hussain et al. 2018). According to some research, dietary supplements containing marigold extract have positive effects on both human and animal growth, survival rates, immunity and inflammation as well as antioxidant defence (Ghafarifarsani et al. 2023). However, there are little data on how different fish species respond to pot marigold supplementation.

4.8 | Lavender

Because of its anti-inflammatory properties, lavender (*Lavandula angustifolia*) is regarded as a medicinal herb (Cardia et al. 2018). It is also considered a medicinal herb because it possesses hepatoprotective (Selmi et al. 2015) and antioxidant (Gülçin et al. 2004) effects when used. Cineole and linalool, which have anti-inflammatory, antioxidant and anti-stress properties, are abundant in lavender extract (Peana et al. 2002; Ciftci et al. 2011). These benefits establish lavender as a possible health enhancer for fish. According to a study on the effects of lavender extract on fish, it improves the phagocytic, respiratory burst and peroxidase activities of head kidney leukocytes in vitro as well as increases their quantity (Fazio et al. 2017).

4.9 | Chamomile

Chamomile (*Matricaria chamomilla*), which belongs to the Asteraceae family, is one of the prominent medicinal plant's natives to southern and eastern Europe (Srivastava et al. 2010). In folk and traditional medicine, it is currently a very popular and frequently used medicinal herb (El-Dakar et al. 2023). One of the key plants for herbal medicine, chamomile (*Chamomilla chamomilla* L.) is used to treat a wide range of illnesses. It is a well-liked remedy for a wide range of illnesses, such as anxiety, sleep disturbances, digestive and intestinal issues, eczema and other skin infections, wound healing, teething discomfort, infantile colic and diaper rash (Heidari and Semin Sarani 2012). The extract of the German chamomile plant (*M. chamomilla*) has 120 different kinds of chemical compounds in it, such as flavonoids, coumarins and chamazulene (Madadi et al. 2022). These compounds' three main active ingredients are alphabisabolol, apigenin and chamazulene (Singh et al. 2011). According to Wu et al. (2011), the compounds in chamomile extract have antibacterial, anti-inflammatory and antioxidant properties.

4.10 | Cajeput

The plant known as cajeput, or *Melaleuca cajuputi*, is widely distributed throughout many tropical regions, such as Indochina, Burma, Malaysia and Indonesia (Al-Abd et al. 2015; Mohamad Khairul Sahimi et al. 2022). Terpenes and flavonoids, two of its main bioactive constituents (Mohamad Khairul Sahimi et al. 2022), have been shown in numerous earlier investigations to possess restorative qualities (Hassan et al. 2023).

4.11 | Nutmeg

Myristica fragrans (Nutmeg) is an edible plant use in preparing many delicacies in different parts of the world. It is known majorly for its alluring fragrance and flavour. Reports also state that it contains ingredients that have high antioxidant and antibacterial properties (Matulyte et al. 2020). Extracts from different parts of some plants have immune-stimulant potentials which could improve the immune status of fish by enhancing both the specific and non-specific defence mechanisms of fish (Moustafa et al. 2020).

4.12 | Clove

Originating in the Indonesian Molucca Islands, clove (*Eugenia caryophyllata*, *Myrtaceae*) is now widely distributed throughout many tropical African countries, including Nigeria (Adeshina et al. 2019). Eugenol, linaol, eugenol acetate, β-caryophyllene, methyl cinnamate, camphor, α-copaene and thymol are among the bioactive compounds present in its buds (Bayoub et al. 2010). These compounds have been shown to have antimicrobial and antifungal properties against a variety of pathogens (Adeshina et al. 2019). Similarly, it has also been reported that clove, *E. caryophyllata* buds contain significant amounts of secondary metabolites such as alkaloids, tannin, flavonoids, saponin and so forth (Begum et al. 2022). The *E. caryophyllata* buds extract (ECBE) contains terpenoids (13.3 mg/100 g), alkaloid (340.0 mg/100 g), steroids (193.3 mg/100 g), tannins (88.3 mg/100 g), lavonoids (66.7 mg/100 g) and saponin (68.3 mg/100 g; Adeshina et al. 2019).

4.13 | Tamarind

The large tree *T. indica* L, also known as the tamarind, is a member of the subfamily *Ceasalpinioideae* and family *Leguminoseae* (Fabaceae). In most tropical and subtropical regions of the world, tamarind is widely grown (Bhadoriya et al. 2011; Parle and Dhamija 2012). Traditionally, tamarind bark or leaves have been applied as a powder, decoction or poultice to cuts, wounds and abscesses, as well as to heal wounds from guinea worm infestations (Devi and Boruah 2020). It has been documented that tamarind is used ethnomedically in many African nations to heal wounds (Baiyeri et al. 2019). Research has indicated that tamarind extracts possess antioxidant (Lim et al. 2013) and antimicrobial properties (Adeniyi et al. 2017; Gumgumjee et al. 2012). While there is little scientific data on *T. indica*'s in vivo antioxidant activities in fish and its ability to promote wound healing, the role of tamarind's antioxidant property in wound healing remains unclear.

5 | Efficacy of Plant Extracts in Fish Wound Healing

The efficacy of medicinal plants in accelerating fish wound healing is becoming more widely acknowledged, these plants provide a cheap, natural substitute for synthetic treatments. Fish wound healing has been demonstrated to be improved by plant extracts, providing a sustainable and all-natural method of managing fish health. These plants improve fish health and wound healing naturally, so when added topically or incorporated into fish diets, they support sustainable aquaculture practices. This section highlights research that has been conducted to assess the suitability of plant extracts in fish wound healing.

The effects of aloe vera on the growth and histological changes in rainbow trout skin were examined in a study, and the findings revealed that feeding aloe vera to fish resulted in a significant increase in goblet cells in the fish epithelium (Heidarieh et al. 2013). Few studies demonstrated the higher mucous cell density in fish treated with various immunostimulants, despite the fact that higher goblet cell density in fish skin and the intestinal tract after a challenge with infectious diseases has been studied (Guardiola et al. 2022; Sheikhzadeh et al. 2019). Fish's mucosa surface mucous cell densities in the skin epidermis and gastrointestinal epithelium create a viscous, hydrated blanket that serves as a sensitive first line of defence against immune system attacks (Ángeles Esteban 2012). Thus, it stands to reason that increasing goblet cell density, particularly when aloe vera is administered in larger doses, would strengthen the rainbow trout's defences against infections (Mehrabi et al. 2019). Higher doses of Aloe vera were found to increase mucous cell number and epidermal thickness in the study (Heidarieh et al. 2013).

Comparing juniperus root extract to antibiotics, previous studies (Önalan and Kankaya 2024) found that the former was more effective in healing experimentally induced incised wounds in yellowtail acei. It was discovered that when using juniper root extract instead of antibiotics, healing happened more quickly. This may be due to its insecticidal, antioxidant, anticancer and antibacterial effects (Isik et al. 2020; Salih et al. 2022). Important characteristics of the extract were also identified, including its ability to stay on the wound and not disperse in a watery environment (Önalan and Kankaya 2024).

Researchers (Bello et al. 2013) investigated the influence of walnut leaf (WL) and onion bulb (OB) residues in the diet on cutaneous wound healing in *Clarias gariepinus*. The experiment lasted 14 days in nine experimental tanks (1.8 m × 2 m × 1.2 m). Nine experimental diets with 40% crude protein contained the following inclusion levels: control (0%), OB2 (0.5%), OB3 (1.0%), OB4 (1.5%), OB5 (2.0%), WL6 (0.5%), WL7 (1.0%), WL8 (1.5%) and WL9 (2.0%). Fish (mean weight: 1 kg) were fed twice daily at 3%

body weight. The percentage healing and daily healing rate on the lateral and caudal sections of male and female *C. gariepinus* were studied at 0, 7 and 14 days. The results showed that fish fed with WL and OB residues performed better than the control. *C. gariepinus* dermal wound recovery was better on the lateral and caudal regions in WL 8 than in the control (98%, 14.00, 80%, 11.43). The results showed that male *C. gariepinus* had better healing than females (100%, 14.29, 82%, 11.71), respectively. Diets containing WL and OB leftovers showed wound-healing qualities and might be used in fish farming. In addition, 1.5% WL residue in fish diet enhances wound healing in *C. gariepinus*.

A study (Adenıyı et al. 2018) looked into the ability of *T. indica* pulp (TP) and leaf (TL) meal to heal wounds as well as the role antioxidant enzymes play in this process in African catfish, *C. gariepinus*. The catfish had 10 mm^2 surgical incisions made aseptically above the pelvic fin and towards the caudal region. As compared to fish in the control groups, the results demonstrated that fish fed diets treated with TP or TL had significantly faster ($p < 0.05$) daily healing rates at the lateral and caudal regions from the sixth to the 12th day. In the tamarind-treated groups, percentage wound healing (PWH) at the caudal and lateral regions was significantly ($p < 0.05$) improved from the sixth day.

Researchers (Vinoth et al. 2018) studied the wound-healing mechanisms in fish muscle tissue after administering plant extracts from *Coscinium fenestratum*, *Azadirachta indica* and *Cynodon dactylon*. The researchers aimed to evaluate how effective these extracts were at promoting tissue regeneration and repair following injury. The results showed that these plant extracts dramatically improved the healing process, with visible increases in tissue repair, reduced inflammation and increased collagen formation in the afflicted muscle tissue. The study found that using these natural extracts as alternative healing agents in aquaculture could provide a long-term solution to treating fish injuries while also enhancing overall fish health and welfare.

Similar to this, research was conducted on African catfish to examine the ability of clove basil (*Ocimum gratissimum*) leaves extract (CBLE) to heal wounds (Abdel-Tawwab et al. 2019). Compared to *C. gariepinus* fed the control diet, *C. gariepinus* fed CBLE-enriched diets showed faster daily healing rates and wound-healing percentages. Fish fed a diet containing 15 g/kg showed complete wound healing (100%) on the 10th and 8th day post-wound (dpw) in both the caudal and lateral regions, respectively. Fish fed a diet containing lower levels of CBLE required longer to heal their wounds completely (Abdel-Tawwab et al. 2019).

To understand the wound-healing potential of clove, *E. caryophyllata*, buds extract (ECBE) on artificially wounded African catfish, researchers (Adeshina et al. 2020) fed four groups of *C. gariepinus* with four isonitrogenous diets (40% crude protein) containing ECBE at levels of 0.0, 5.0, 10.0 or 15.0 g/kg. Fish (61.5 ± 2.51 g) were lacerated (1 cm long) in both the caudal and lateral areas and randomly assigned to 12 rectangular tanks. The fish were fed one of the experimental diets in triplicate for 14 days, with wound-healing closure and histological changes monitored. Fish fed ECBE-supplemented diets healed faster and at a higher percentage than those fed a control diet. The wound-healing rate and percentages were delayed in fish fed control or low-ECBE diets. However, fish fed a diet containing 15 g ECBE/kg achieved total/highest healing (100%) on the 12th dpw in lateral and 10th dpw in caudal regions, whereas fish fed the control diet had the lowest healing rate (6.29%/day) and percentage (88%) in lateral and caudal regions on the 14th dpw. In addition, the lesion healed more rapidly in the caudal region than the lateral, with early tissue regeneration and normal oriented keratinocytes in the epidermal and muscle layers. As a result, adding 15 g ECBE/kg diet to African catfish diets could be utilised in fish farming to speed up wound healing and prevent wound-related mortality and infection.

In a different investigation, scientists assessed *Melaleuca cajuputi* leaf extract (MCLE)'s capacity to heal artificially injured *C. gariepinus* wounds (Hassan et al. 2023). The fish were left to swim in the treatment solutions for 30 days after being artificially injured (i.e., with a laceration measuring 1 cm in length and 0.4 cm in depth) on both lateral sides (Hassan et al. 2023). Findings showed that, in comparison to the control, MCLE treatments accelerated epidermal cell migration, covering and proliferation as early as 1 h after the artificial injury was applied (Hassan et al. 2023). The MCLE treatment at 12.7 and 25.4 mg/L closed the wounds and started the basement membrane's formation at 3 h, the tetracycline and control treatments did not reveal these conditions until 6 h later (Hassan et al. 2023).

A study (Albaladejo-Riad et al. 2022) reported that supplementing the diet of gilthead seabream with 100 (SF100 diet) mg/kg of silk microparticles can be considered an appropriate feed addition for improving wound healing. This was after the effects of food supplementation with silk fibroin (SF) microparticles on wound healing in gilthead seabream (*Sparus aurata*) skin were investigated. The control diet was supplemented with SF values of 0 (control), 50 (SF50 diet) and 100 (SF100 diet) mg/kg to produce three experimental diets fed to seabream for 30 days. After 7 days post-wounding, skin mucus immunity, macroscopic wound closure and skin regeneration were investigated at the microscopic and genetic levels. The results showed that fish fed SF100 did not exhibit the declines in protease and IgM levels seen in the skin mucus of wounded fish fed the control diet. Macroscopic results showed that dietary SF100 considerably enhanced wound closure ratios compared to those raised in the control group. At the microscopic level, changes in the morphology of keratocyte cells were visible in the injured fish. Furthermore, the intercellular spaces between epidermal cells and their proliferation in the epidermis, as well as the presence of blood vessels in the dermis, were significantly higher in the skin of fish fed the SF100 diet and sampled at 7 dpw than in the skin of fish fed the control or SF50 diets. Furthermore, statistically significant increases and decreases in the RNA:DNA ratio were detected in fish fed the control and SF100 diets, in both non-wounded and wounded fish. Interestingly, dietary SF100 supplementation boosted skin cell proliferation, inflammatory activity and expression of key genes involved in tissue healing and ECM formation.

Researchers (Chingjit and Kritsanaphan 2024) evaluated the wound-healing capacity of *Xylocarpus granatum* bark extract in *Betta splendens*. The extract was produced using the decoction method. The resulting extract was then applied to betta fish wounds at doses of 60, 120 and 180 ppm, respectively. These treatment groups were compared to a positive control group that received 15 ppm oxytetracycline and a negative control group that received no therapy over a 21-day period. The results showed that the groups treated with 60 or 120 ppm of *X. granatum* bark extract healed the fastest. The 60 ppm concentration showed higher survival rates (85.0 ± 4.3%) among treated fish. In particular, both the negative and positive control groups had complete wound healing by 21 days, and their survival rates were among the lowest. In terms of healing effects on different tissue layers, muscle tissue repair took longer in the 60 ppm group than in the 120 and 180 ppm groups. However, for connective tissue, dermis, epidermis and scale tissues, the 60 ppm treatment group had the fastest wound-healing rates. Based on these findings, *X. granatum* bark extract has potential as a wound-healing agent for *B. splendens*, particularly at a concentration of 60 ppm.

The bioactive components included in these extracts, such as flavonoids, tannins and alkaloids, can help with healing by increasing cell proliferation, collagen formation and angiogenesis—all of which are important steps in tissue repair. Furthermore, as compared to synthetic alternatives, these plant-based solutions frequently have fewer side effects and are less toxic, making them ideal for a wide range of fish species in various aquaculture systems. The findings from the studies reported in this section by far and large demonstrate that applying various plant extracts in the wound healing of fish could be beneficial to the aquaculture industry.

6 | Factors Influencing Efficacy

6.1 | Wound Type and Severity

Plant extracts may be more effective for certain types of wounds in fish (e.g., bacterial, fungal or parasitic infections) or severity levels (Zhang et al. 2022). Wound type and severity are factors affecting the efficacy of plant extracts in fish wound healing as different wounds require specific treatments (El-Ashram et al. 2021). Various wound types (e.g., abrasions, lacerations, ulcers) respond better to specific bioactive compounds or combinations (Ibrahim et al. 2018). More severe wounds on fish require longer treatment periods, affecting the efficacy of plant extracts (Alam et al. 2014). Wound severity influences the depth of bioactive compound penetration, affecting efficacy in fish wound healing (Alam et al. 2014). Moreover, different wound-healing stages (e.g., inflammation, proliferation, remodelling) require specific bioactive compounds or combinations as the size of wound the efficacy of plant extracts, as larger or more complex wounds may require different treatments (Li et al. 2022). Additionally, the severity of wounds can impact fish stress and immunity, affecting the efficacy of plant extracts in supporting wound healing (Rajapaksha et al. 2020). Considering wound type and severity ensures targeted treatment with plant extracts, enhancing efficacy and supporting optimal wound healing in fish (Sharma et al. 2022).

6.2 | Water Quality and Temperature

Environmental factors can impact the efficacy of plant extracts and wound-healing processes in fish (Awad and Awaad 2017; Figure 4). Water quality and temperature are factors affecting the efficacy of plant extracts in fish wound healing as water temperature and quality affect the bioavailability of bioactive compounds in plant extracts promoting wound healing in fish (Faheem et al. 2022). The temperature of water influences the absorption rate and solubility of bioactive compounds through fish skin and scales impacting the efficacy in use for promoting healing in fish wounds (Tang et al. 2020). Additionally, the quality of water and temperature of water for fish can cause fish stress which could also affect the immune system impacting wound healing and plant extract efficacy (Mahmoud et al. 2021). The efficacy of bioactive substances in plant extracts can be diminished by oxidation and degradation caused by variations in water temperature and quality, affecting wound-healing process in fish (Faheem et al. 2022). The effectiveness of plant extracts in treating fish wounds is dependent on the ideal temperature and water quality, whereas less-than-ideal conditions can lessen the effectiveness of treatment (Lieke et al. 2020).

6.3 | Quality and Potency of the Extract

Variability in extraction methods, plant material and storage conditions can impact the efficacy of plant extracts in promoting wounds in fish (Muthukumar et al. 2014). The effectiveness of plant extracts in healing fish wounds is influenced by potency and quality. The plant material used has an impact on the extract's efficacy because lower quality material could have fewer bioactive components (Makkar et al. 2007). The lack of standardisation in plant extract production can lead to variable potency and efficacy between batches and products (Govindaraghavan and Sucher 2015). Poor quality control can result in contamination or adulteration, reducing efficacy and potentially harming fish. Additionally, the variations in potency can impact the effective dosage and concentration of plant extracts, affecting the efficacy of plant extracts in fish wound healing (Tangendjaja 2022). Different fish species and sizes may require specific potencies and qualities of plant extracts for optimal efficacy in wound healing (Soltani et al. 2019). Ensuring high-quality and potent plant extracts is crucial for effective wound healing in fish, as variations in quality and potency can significantly impact treatment efficacy (Lieke et al. 2020).

6.4 | Concentration and Dosage

Incorrect concentrations or dosages can lead to in effective or toxic outcomes in fish (Jebet 2018). Concentration and dosage determine the number of bioactive compounds delivered to the wound site in fish. Moreover, fish respond differently to varying concentrations and dosages of plant extracts, with optimal levels eliciting the best response (Awad and Awaad 2017). Excessive levels or dosages of plant extracts can lead to toxicity and adverse effects, hindering wound healing in fish (Chahardehi et al. 2020). Fish of various species and sizes would require variable concentrations and doses of plant extracts due to varying body mass and metabolic rates. Therefore, the concentration and dosage of plant extracts must be altered according to wound size and severity to ensure efficient therapy in fish (Bulfon et al. 2015). Concentration and dosage can influence the wound micro-environment, impacting the activity and stability of bioactive compounds aiding in the wound healing of fish (Gaspar-

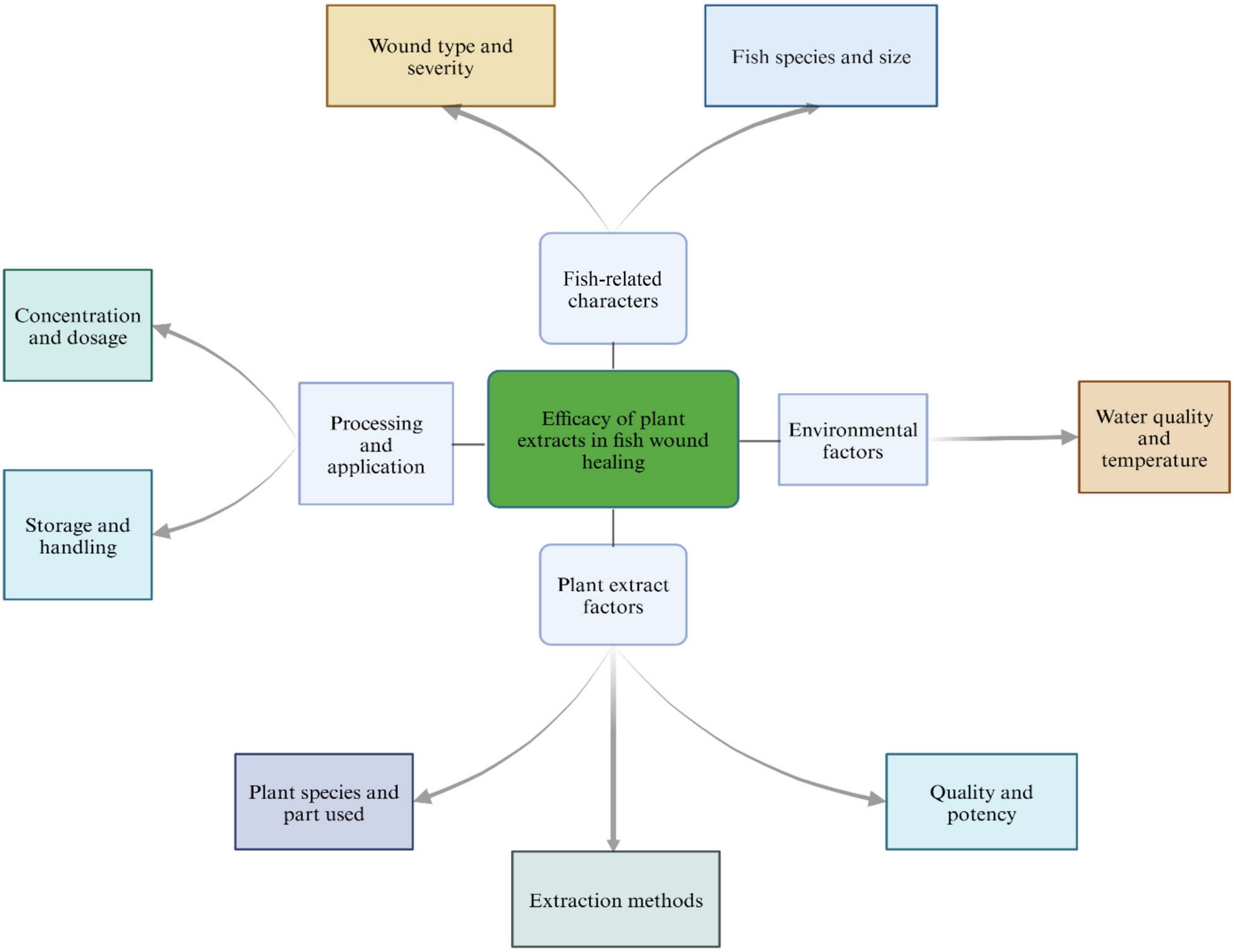

FIGURE 4 | Factors influencing efficacy of plant extracts in fish wound healing.

Pintiliescu et al. 2019). Optimising concentration and dosage ensures the effective delivery of bioactive compounds, promoting efficient wound healing and minimising potential adverse effects in fish (Gaspar-Pintiliescu et al. 2019).

6.5 | Plant Species and Part Used

Different plant species and parts (e.g., leaves, roots, bark) have varying bioactive compounds and efficacies in wound healing (Sharma et al. 2021). Different plant species and parts contain unique bioactive compounds, influencing efficacy and potency (Guo et al. 2020). Various plant species and parts offer diverse phytochemicals, affecting the treatment of different wound types and severity (Vitale et al. 2022). The plant species and part used may be selected based on the type and severity of the wound (Näslund and Johnsson 2016). Using the right plant species and part ensures the optimal bioactive compound profile for effective fish wound healing, while incorrect selection may lead to reduced efficacy or adverse effects (El-Ashram et al. 2021).

6.6 | Extraction Methods

Solvents temperatures and extraction times can influence the bioavailability and stability of bioactive compounds (Usman et al. 2022). The extraction method of plant extract is a factor affecting efficacy in fish wound healing as different extraction methods can influence the amount and type of bioactive compounds extracted (Idris and Mohd Nadzir 2021). Moreover, extraction methods can selectively extract specific bioactive compounds, affecting efficacy in the process of wound healing in fish (Idris and Mohd Nadzir 2021). The type of bioactive compounds that are extracted can be affected by the polarity of the extraction solvent since the process of extraction can either activate or inhibit enzymes, which influences the activity of bioactive compounds (Ghenabzia et al. 2023). Extraction methods can influence the particle size of the extract, affecting bioavailability and the method could impact standardisation and consistency of the extract (Servat-Medina et al. 2015). Extraction methods can introduce contaminants or impurities, affecting efficacy and safety for use in the fish wound-healing process (Baduel et al. 2015). The most effective extraction technique varies based on the type of wound, bioactive chemicals and plant species. This can have a substantial impact on how well plant extracts treat fish wounds (Idris and Mohd Nadzir 2021).

6.7 | Storage and Handling

Improper storage and handling can degrade or inactivate bioactive compounds (Stéphane et al. 2021). The effectiveness of plant extracts in healing fish wounds is influenced by storage and handling practices. Improper storage and handling can cause bioactive components to degrade, which lowers the extracts' healing efficiency (Vlčko et al. 2022). The stability and potency of bioactive compounds can be affected by oxidation brought on by exposure to air, light or heat. However, improper handling and storage might introduce contaminants, decreasing their efficacy and perhaps endangering fish (Nishad 2022). The potency and stability of bioactive compounds can be impacted by storage at the wrong temperature, and insufficient storage conditions can cause moisture and humidity variations (Rezvankhah et al. 2020). Insufficient storage conditions have the potential to encourage microbial growth, which can diminish efficacy and endanger fish. Additionally, this process might shorten the shelf life of plant extracts, which can eventually impact efficacy (Nishad 2022). Exposure to direct sunlight or UV light can degrade bioactive compounds (Altemimi et al. 2017).

6.8 | Fish Species and Size

The different size of fish and species may respond differently to plant extracts due to varying physiological and metabolic rates (Sopinka et al. 2016). The effectiveness of plant extracts in fish wound healing is influenced by the size of the fish and species as their distinct metabolic rates impact the uptake and application of bioactive chemicals (Chakraborty and Hancz 2011). Fish size influences the amount of extract required to effectively treat wounds (El-Ashram et al. 2021). The size and kind of fish have an impact on the structure of their skin and scales, which influences how well bioactive substances are absorbed and penetrated (Firmino et al. 2021). The natural wound-healing rate, which affects the efficiency of plant extracts, is generally influenced by the type of fish (species) as well as its size (Awad and Awaad 2017).

The sensitivity of fish to bioactive chemicals varies by species and size, affecting efficacy and potential toxicity (Gatlin et al. 2007). The recommended dose and concentration of plant extracts for successful treatment vary according to fish weight and breed (Awad and Awaad 2017). Different kinds of fish and sizes have different nutritional requirements, which influences the efficacy of plant extracts in wound healing (Van Doan et al. 2019). Considering the fish species and size ensures optimal dose, efficacy and safety of plant extracts in fish wound healing, as different species and sizes respond differently to therapy (Van Doan et al. 2019).

7 | Challenges and Limitations of Applying Plant Extracts for Wound Healing

Applying plant extracts for wound healing in fish can come with several challenges and limitations, including:

7.1 | Bioavailability

Applying plant extracts to fish wounds presents a difficulty and constraint regarding bioavailability because certain plant extracts may not be water-soluble, which reduces absorption and bioavailability (Bulfon et al. 2015). In addition to being problematic, uncertainty regarding the uptake and dispersion of plant chemicals in fish tissues can also be dangerous (Bulfon et al. 2015). Plant extracts may require lipid solubility to penetrate fish skin and scales, which can be challenging (Adeoti and Hawboldt 2014). Moreover, fish body fluids have a specific pH and ionic strength, which can affect bioactive compound absorption and bioavailability (Kültz 2015). Bioactive compounds can undergo oxidation and hydrolysis, reducing bioavailability (Dima et al. 2020).

7.2 | Toxicity

Possibly poisonous or harmful to fish health, particularly in high quantities or over an extended period of time. When using plant extracts to treat fish wounds, toxicity is a problem and a constraint since some of the bioactive chemicals in the plants can be poisonous to fish in large amounts (Ferraz et al. 2022). Plant extracts can cause acute toxicity, leading to fish mortality and a long-term exposure to plant extracts can cause chronic toxicity, affecting fish health for a period (Ferraz et al. 2022). Bioactive compounds from plant extracts can bioaccumulate in fish tissues, leading to toxicity (Noureen et al. 2023). Water quality and environmental factors can enhance toxicity as poor water quality will have negative effects on the fish (Bhateria and Jain 2016). Plant extracts can leave residues in fish tissues, potentially accumulating and causing toxicity (Syahidah et al. 2015).

7.3 | Standardisation

A lack of standardised extraction and processing methods, leading to inconsistent product quality (Nafiu et al. 2017). Standardisation is a challenge and limitation in applying plant extracts for wound healing in fish as plant material can vary in quality, composition and bioactive compound content (Hussain et al. 2017). The compositions of bioactive compounds and concentration can vary depending on the extraction technique used. Plant extracts can contain varying levels of bioactive compounds, affecting efficacy and toxicity (Altemimi et al. 2017). Optimal dosages of plant extracts for fish wound healing are not well established (Bulfon et al. 2015). The lack of standardisation in fish wound-healing models makes it challenging to compare outcomes and there are no established therapy methods for using plant extracts to repair fish wounds (Masson-Meyers et al. 2020). Regulatory frameworks for plant extract use in aquaculture are often Inadequate or lacking, therefore causing a lot of problems with regards to standardisation of the extract.

7.4 | Delivery Methods

Difficulty in delivering plant extracts directly to the wound site, especially in aquatic environments (Pereira and Bartolo 2016). Delivery method is a challenge and limitation in applying plant extracts for wound healing in fish as delivering plant extracts directly to the wound site can be challenging and might not be targeted (Kumala et al. 2018). Plant extracts may not be absorbed efficiently through fish skin or scales depending on the delivery method. Plant extracts can degrade quickly in water, reducing efficacy in the healing of fish wounds (Reverter et al. 2014). Optimal delivery methods for plant extracts in fish wound healing are not well established and can be performed in ignorance (Masson-Meyers et al. 2020). Scaling up delivery methods for large-scale aquaculture can be challenging (Boyd et al. 2020).

7.5 | Interactions With Other Treatments

Interaction with other treatments is a challenge and limitation in applying plant extracts for wound healing in fish as plant extracts may interact with other treatments, enhancing or reducing their efficacy (Awad and Awaad 2017). Interactions between plant extracts and other aquaculture treatments are not well understood (Olusola et al. 2013). Plant extracts may interact with other treatments, causing adverse reactions or toxicity (Mensah et al. 2019). Interactions with other treatments may reduce the efficacy of plant extracts and increase the toxicity of plant extracts (Ahmadifar et al. 2021). The most effective combination therapy with plant extracts and other therapies is not well known, and interactions with other therapies may lead to drug-resistant microbes (Pohl and Kong Thoo Lin 2018). Regulatory guidance on interactions between plant extracts and other treatments is limited (Sahoo et al. 2010). Addressing these challenges and limitations is crucial to ensure the safe and effective use of plant extracts in combination with other treatments for fish wound healing (Tiamiyu et al. 2023).

7.6 | Limited Research

Limited scientific research and understanding of plant extract effects on fish wound healing (Ibrahim et al. 2018). Limited research is a challenge and limitation in applying plant extracts for wound healing in fish as limited research means there is insufficient scientific evidence to support the use of plant extracts for fish wound healing. The mechanisms by which plant extracts exert their effects on fish wound healing are not well understood (Ibrahim et al. 2018). Potential interactions between plant extracts and other aquaculture treatments have not been extensively studied (Tadese et al. 2022). There has not been much research conducted on the long-term effects of plant extracts on fish wound healing or the impact of plant extracts on various fish species (Bulfon et al. 2015).

7.7 | Water Quality

Water quality variability poses a barrier and limits the application of plant extracts for fish wound healing. The stability and effectiveness of plant extracts can be impacted by large variations in water quality (Awad and Awaad 2017). Water pH and temperature can affect the bioavailability and stability of plant extracts affecting wound healing in fish (El-Ashram et al. 2021). Water hardness and mineral content can affect the absorption and efficacy of plant extracts (Awad and Awaad 2017). Moreover, water flow and circulation can affect the delivery and distribution of plant extracts in its application (Masoomi Dezfooli et al. 2019). Plant extracts may have limited solubility in water, affecting their delivery and efficacy (Abubakar and Haque 2020). Maintaining consistent water conditions can be challenging, affecting the efficacy and reliability of plant extract treatments (Elfitasari and Albert 2017).

7.8 | Fish Behaviour and Stress

Fish behaviour and stress are challenges and limitations in applying plant extracts for wound healing in fish as stress can exacerbate wounds, worsening wounds and impede healing. Stress can reduce the absorption of plant extracts (Sveen 2018). Stress or wounds can affect feeding behaviour, impacting treatment delivery. Handling fish for treatment can cause additional stress (Noble et al. 2012). Monitoring fish behaviour and stress can be difficult in large-scale aquaculture settings (Noble et al. 2012). Addressing these challenges and limitations requires considering fish behaviour and stress when designing treatment protocols and monitoring fish welfare to ensure the effective and safe use of plant extracts for wound healing in fish (Gabriel 2016).

8 | Conclusions

Plant extracts offer a natural and sustainable approach to enhancing fish wound healing due to their anti-inflammatory, antioxidant and antimicrobial properties. While they show great potential in reducing infections and promoting tissue repair, challenges remain in standardisation, bioavailability, regulatory approvals and environmental impact. Future research should focus on transcriptomic and proteomic analyses to identify gene expression changes and protein interactions during wound healing with plant-based treatments. Integrating plant-based treatments into aquaculture can reduce antibiotic dependence, improve fish health and promote sustainability, making them a viable alternative for long-term disease management in aquaculture systems.

Author Contributions

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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