Mediterranean Journal of Basic and Applied Sciences (MJBAS)
Volume 9, Issue 2, Pages 180-203, April-June 2025

Nature in a gel: Harnessing plant extracts in hydrogels for a greener biotechnology

María I. León-Campos[1], Lesly Katleya Usme-Duque[1], Valeria G. Oyervides-Guajardo[1], Dirce S. Gomez-Galicia[1], Miguel A. Medina-Morales[2], Tirso E. Flores-Guía[1], Lucía F. Cano-Salazar[1], Denis A. Cabrera-Munguia[1] & Jesús A. Claudio-Rizo[1*]

[1]*Department of Advanced Materials, Faculty of Chemical Sciences, Autonomous University of Coahuila, Blvd. Venustiano Carranza S/N, República, 25280 Saltillo, Coahuila, México.* [2]*Department of Environmental Biotechnology, Faculty of Chemical Sciences, Autonomous University of Coahuila, Blvd. Venustiano Carranza S/N, República, 25280 Saltillo, Coahuila, México. Email: jclaudio@uadec.edu.mx*[*]

DOI: https://doi.org/10.46382/MJBAS.2025.9216

Article Received: 02 April 2025 *Article Accepted: 07 June 2025* *Article Published: 13 June 2025*

ABSTRACT

Hydrogels are three-dimensional, water-absorbing polymeric networks that are highly suitable for biomedical and pharmaceutical applications, particularly in drug delivery and tissue engineering. Their physicochemical properties, including polymer composition and cross-linking density, can be precisely tuned to meet specific functional requirements. Incorporating plant extracts into hydrogels enhances the stability, solubility, and bioavailability of bioactive compounds, enabling their controlled release. Various encapsulation strategies have been developed to protect these compounds, broadening their potential in the pharmaceutical, cosmetic, and food industries. Hydrogels loaded with plant extracts also demonstrate intrinsic antioxidant and antibacterial activities, making them promising candidates for applications in wound healing, skin hydration, food preservation, and sustainable agriculture. Moreover, recent advancements in nanotechnology have further refined the performance of these systems, improving their stability, therapeutic efficacy, and potential contributions to environmentally sustainable practices.

Keywords: Hydrogels; Plant Extracts; Encapsulation Techniques; Nanotechnology; Biomedical and Pharmaceutical Applications; Tissue Engineering; Polymeric Networks in Biotechnology; Drug Delivery; Controlled Release; Antioxidant; Antibacterial.

1. Introduction

Hydrogels are three-dimensional polymeric networks that can absorb and retain substantial amounts of water while preserving their structural integrity. This unique characteristic makes them highly suitable for biomedical and pharmaceutical applications, particularly in drug delivery systems and tissue engineering. The versatility of hydrogels stems from their tunable properties, which are influenced by factors such as polymer composition, cross-linking density, and the presence of functional agents *(Khan et al., 2024)*.

When employed for the immobilization of plant extracts, hydrogels provide a hydrated environment that facilitates interaction with bioactive compounds, thereby regulating their release and enhancing stability *(Sarkar & Levi-Polyachenko, 2020)*. The physicochemical and mechanical properties of hydrogels are crucial in determining their efficacy in these applications. Various characterization techniques, such as Fourier Transform Infrared Spectroscopy (FTIR), rheology, and scanning electron microscopy (SEM), are employed to evaluate the stability, composition, and structural properties of hydrogels *(Song et al., 2022)*.

Encapsulating plant extracts within hydrogels improves their stability, solubility, and bioavailability, while enabling controlled release. Several encapsulation techniques are available, such as emulsion solvent evaporation, in situ polymerization, nanoprecipitation, microencapsulation, and ionic gelation. These methods differ in their processing and composition, but they share the common goal of protecting bioactive compounds and enhancing their utility in pharmaceuticals, cosmetics, and the food industry *(Reddy et al., 2022)*. Studies have demonstrated that hydrogels loaded with plant extracts exhibit enhanced antioxidants, antibacterial, and wound-healing properties, making them valuable in both biomedical and industrial applications *(He et al., 2024)*.

Mediterranean Journal of Basic and Applied Sciences (MJBAS)
Volume 9, Issue 2, Pages 180-203, April-June 2025

Plant extract encapsulated hydrogels offer a sustainable and versatile solution for a wide range of applications in biomedicine, cosmetics, food, and agriculture. Their bioactive properties such as antioxidant, antimicrobial, antiinflammatory, and growth stimulating effects are further enhanced by the controlled, sustained release facilitated by hydrogels' environmental stimuli-responsive mechanisms *(Chelu, 2024)*. In medicine, these hydrogels promote wound healing and optimize drug delivery; in cosmetics, they enhance hydration and anti-aging effects *(Choi et al., 2024)*; in the food industry, they support preservation and packaging *(Leyva-Jiménez et al., 2023)*; and in agriculture, they provide eco-friendly alternatives to conventional pesticides and fertilizers *(Ali et al., 2024)*. Advances in nanotechnology have further improved stability, bioavailability, and targeted delivery of plant extracts, positioning hydrogels as an innovative and environmentally friendly tool across multiple industries. Nanomaterials are increasingly being incorporated into hydrogels, combining nanotechnology with plant extracts to enhance the stability, therapeutic efficacy, and controlled release of bioactive compounds *(Kawee-ai, 2025)*. These advancements have led to improved drug delivery systems and environmental applications, such as contaminant removal and sustainable agricultural practices. Nanohydrogel technology also enhances the bioavailability and stability of plant extracts, offering new solutions in pharmaceutical, biomedical, and environmental sectors. Key applications include wound healing, drug delivery, and eco-friendly remediation *(Delgado-Pujol et al., 2025)*.

1.1. Study objectives

The following are the main objectives:

(i) To investigate the physicochemical and structural properties of hydrogels used for the immobilization of plant extracts.

(ii) To evaluate interactions between plant extracts and hydrogels matrices, including physical and chemical immobilization methods

(iii) To determine the functional enhancement implanted by plant extract incorporation.

(iv) To investigate the impact of incorporating plant extracts into hydrogels.

(v) To assess the applicability of encapsulated plant extracts in hydrogels for target used in wound healing, infection control and crop biostimulation.

2. Properties and Characterization of Hydrogels

Hydrogels are three-dimensional polymeric networks capable of absorbing and retaining significant amounts of water. When swollen, they can mimic the mechanical and physical properties of biological tissues, while maintaining structural integrity due to the chemical or physical cross-linking mechanisms involved in their synthesis *(Ho et al., 2022)*. Hydrogels used for the immobilization of plant extracts possess a highly hydrated, three-dimensional matrix that facilitates interactions with bioactive compounds and enables their controlled release *(Mishra et al., 2021)*. The properties of these hydrogels particularly their chemical composition and mechanical behavior are determined by multiple factors, including the type of polymer used, the degree of cross-linking, and the presence of functional groups that allow for the incorporation of plant-derived molecules *(Kaith et al., 2021)*. Hydrogels can be synthesized from natural polymers such as alginate, cellulose, chitosan, and collagen, which confer high biocompatibility and biodegradability. Alternatively, synthetic polymers like polyethylene glycol (PEG) and polyacrylamide provide enhanced control over mechanical properties and long-term stability *(Kaur et al., 2024)*. Blending natural and synthetic polymers enables fine-tuning of hydrogel characteristics to meet the specific demands of biomedical applications.

The immobilization of plant extracts within hydrogels occurs through physical or chemical interactions with the polymeric matrix. Physical incorporation is typically mediated by hydrogen bonding and *Van der Waals* forces, which allow for the entrapment of bioactive compounds without altering their molecular structure *(Huynh et al., 2023; Kusjuriansah et al., 2024)*. In contrast, chemical immobilization involves covalent bonding facilitated by cross-linking agents, resulting in improved system stability and more precise control over the release kinetics of the encapsulated extracts *(Kawee-ai, 2025)*.

2.1. Characterization of hydrogels

At the structural level, hydrogels possess a porous network whose morphology directly influences their water absorption capacity, the diffusion of encapsulated plant extracts, and the mechanical strength of the material. These features are critical for determining the stability of the immobilized extracts and their controlled release under physiological conditions *(Ramírez-Brewer et al., 2025)*. Proper characterization of hydrogels is essential to ensure their functionality in biomedical and therapeutic applications. Achieving the desired structure requires the use of analytical techniques that assess stability, composition, and performance *(Azeera et al., 2019)*. Table 1 summarizes some of the most commonly employed characterization methods in hydrogel development, which are particularly useful for evaluating the presence of plant extracts and their interactions within the polymeric matrix.

Table 1. Characterization techniques for hydrogels with plant extracts *(Azeera et al., 2019)*

Type of characterization	Characterization techniques	Function
Physico-chemical characterization	Fourier transform infrared spectroscopy (FTIR)	Detects functional groups and chemical linkages. Enables detection of changes in the chemical structure of the hydrogel after immobilization of plant extracts.
	Nuclear magnetic resonance (NMR)	Analysis of the molecular structure of the bioactive compounds of the plant extract within the hydrogel, mobility of the compounds and release kinetics.
	X-Ray diffraction (XRD) analysis	Evaluates whether the incorporation of the extract modifies the internal structure of the hydrogel, determining the crystalline or amorphous state.

	Rheology	Evaluates the effect of the immobilized extract on the viscosity, flexibility and structural integrity of the hydrogel.
Structural characterization	Scanning electron microscopy (SEM)	Analysis of the surface structure and porosity of the hydrogel, along with the dispersion of the plant extract.
Thermal characterization	Differential scanning calorimetry (DSC)	Analysis of the thermal interaction between extract and hydrogel by melting point, crystallization, and glass transition.
	Thermo gravimetric analysis (TGA)	Identifies potential degradation of the extract through mass loss during thermal processing.

Studies have demonstrated that the incorporation of plant extracts into hydrogels can significantly enhance their functional properties. Notable improvements include increased flexibility, enhanced biocompatibility, and superior water retention capacity. Additionally, these composite materials can effectively absorb wound exudates, creating a moist environment that supports and accelerates the healing process. Owing to these features, plant-extract-enriched hydrogels closely mimic the extracellular matrix, positioning them as promising candidates for the development of advanced wound dressings *(Y.-Y. Lin et al., 2021)*.

3. Plant extracts and methods of production

Plant extracts contain a wide array of bioactive compounds with significant potential for biomedical applications, particularly in tissue engineering and regenerative medicine *(Nisa et al., 2024)*. These compounds can be used to enhance various properties of hydrogels, most notably by improving their biocompatibility. The extraction of bioactive molecules from plant sources depends on the chemical nature of the target compound and the complexity of the plant matrix.

Common extraction methods include traditional solvent-based techniques using ethanol or methanol, as well as advanced, green technologies such as ultrasound-assisted extraction, microwave-assisted extraction, and supercritical fluid extraction. These modern approaches offer improved efficiency and reduce reliance on toxic solvents *(Valisakkagari et al., 2024)*.

Furthermore, biotechnological strategies such as fermentation and enzyme-assisted extraction have gained attention for their ability to increase the accessibility and yield of active compounds, thereby facilitating their subsequent entrapment in hydrogel systems *(Gavan et al., 2022)*. The choice of extraction technique plays a crucial role in determining the quality of the extracted compounds, directly impacting their bioavailability, stability, and potential for controlled release in biomedical contexts.

Figure 1 illustrates the main categories of bioactive compounds—such as essential oils, phytochemicals, and phytohormones—that can be derived from plant extracts, along with the most commonly employed extraction techniques for obtaining each type.

3.1. Bioactive properties of the extracts

3.1.1. Extracts with antioxidant properties

The antioxidant properties of plant extracts are primarily attributed to their rich composition of phenolic compounds and flavonoids, which play a key role in mitigating oxidative stress, promoting wound healing, and supporting tissue regeneration *(Kędzierska et al., 2023)*. Flavonoids such as resveratrol, chlorogenic acid, and quercetin have been shown to inhibit pro-oxidative enzyme activity while enhancing the function of endogenous antioxidant enzymes, including superoxide dismutase (SOD) and catalase, thereby exerting potent antioxidant effects *(Zulkefli et al., 2023).* When incorporated into hydrogels, these bioactive compounds benefit from a controlled and sustained release profile, which not only maximizes their therapeutic efficacy but also minimizes premature degradation. Furthermore, their capacity to neutralize free radicals contributes to reduced cellular damage and facilitates the repair of tissues affected by wounds or chronic inflammatory conditions *(Fang et al., 2024).*

3.1.2. Extracts with antimicrobial properties

The antimicrobial activity of plant extracts is largely attributed to the presence of tannin-type phenolic compounds and essential oils, which enhance the effectiveness of hydrogels in preventing or treating wound infections by inhibiting the growth of pathogenic microorganisms *(Kusjuriansah et al., 2024)*. Studies have shown that the synergistic interaction among various bioactive compounds confers prolonged antimicrobial effects, thereby accelerating wound healing and improving overall therapeutic outcomes when using plant-extract-loaded hydrogels, particularly those enriched with polyphenols *(Li et al., 2022)*. Several mechanisms have been proposed to explain the antimicrobial action of these compounds, including: (1) disruption of cell membrane integrity and permeability; (2) inhibition of enzymatic pathways critical to protein synthesis, leading to cellular dysfunction; (3) induction of oxidative stress through the generation of reactive oxygen species (ROS); and (4) prevention of biofilm formation, which is essential for microbial survival and resistance *(Dubourg et al., 2015; Zhao et al., 2023).*

3.1.3. Extracts with anti-inflammatory properties

Certain plant extracts offer an effective strategy for modulating the inflammatory response in wounds and damaged tissues. These bioactive compounds can reduce the production of proinflammatory cytokines, thereby minimizing swelling and pain and fostering an environment conducive to cellular regeneration *(Micale et al., 2020)*. The use of hydrogels for the controlled release of such extracts enables localized and sustained delivery, enhancing their therapeutic efficacy. Notably, extracts with antioxidant properties also contribute to inflammation reduction by neutralizing ROS, further limiting tissue damage *(Li et al., 2022)*. Key anti-inflammatory agents in plant extracts include flavonoids and alkaloids, which target critical inflammatory signaling pathways. For instance, mitragynine—an alkaloid—has demonstrated the ability to suppress inflammation by inhibiting the enzymes 5-lipoxygenase (5-LOX) and cyclooxygenase-2 (COX-2), thereby reducing the synthesis of inflammatory mediators such as prostaglandins and leukotrienes *(Iqbal et al., 2025; Rahmawati et al., 2024)*.

Additionally, certain polyphenols have been shown to inhibit the activation of nuclear factor kappa B (NF-κB), subsequently decreasing the expression of proinflammatory cytokines such as tumor necrosis factor-alpha (TNF-α) and interleukin-6 (IL-6) *(Zeng et al., 2025)*. Hydrogels, due to their porous, hydrated three-dimensional networks, provide an ideal platform for stabilizing these bioactives and enhancing their bioavailability, offering promising potential for the treatment of inflammation-related conditions.

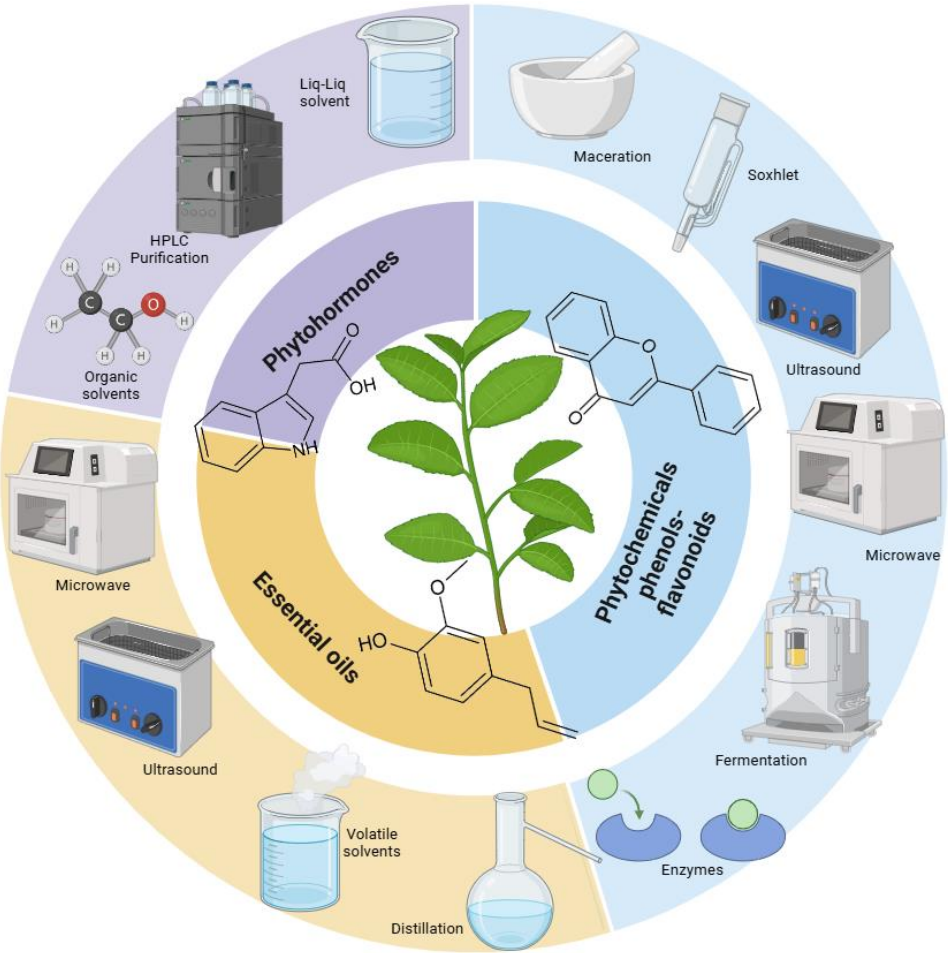

Figure 1. Plant bioactive compounds incorporated in hydrogels and extraction methods

3.1.4. Extracts with cell growth stimulating properties

The incorporation of growth- or proliferation-stimulating extracts into hydrogels represents an innovative approach with significant potential, particularly in agriculture, by improving the efficiency of biostimulant absorption in plants and contributing to more sustainable agricultural practices. These stimulating properties are primarily attributed to substances such as plant hormones, which regulate key biological processes. The most commonly utilized plant hormones include auxins, gibberellins, and cytokinins, all of which play vital roles in plant growth regulation, cell division, and environmental response *(Sampedro-Guerrero et al., 2023)*. Encapsulating phytohormones within hydrogels for agricultural applications enables the controlled and gradual release of these growth regulators, optimizing their uptake by plants while minimizing premature degradation. Thanks to their porous structure and high water retention capacity, hydrogels release phytohormones in response to environmental cues, such as soil moisture and pH, ensuring sustained availability. Additionally, hydrogels protect phytohormones from photodegradation and microbial activity, extending their efficacy and reducing the frequency of reapplication *(Kudasova et al., 2021)*. By maintaining an optimal microenvironment around the plant roots, hydrogels facilitate the efficient absorption of phytohormones, promoting essential growth processes, such as seed germination, cell elongation, and flowering *(Skrzypczak et al., 2019)*.

4. Methods of encapsulation of plant extracts in hydrogels

Plant extracts contain a wide range of bioactive compounds with various therapeutic and protective properties, including anticancer, antibiotic, antioxidant, antifungal, antiparasitic, and antiviral effects. However, their extraction often involves organic solvents, which can complicate formulation and limit their direct application in human use *(Armendáriz-Barragán et al., 2016)*. Encapsulation is an emerging technique that involves enclosing active compounds within a matrix or membrane in particulate form. This process enhances the stability, controlled release, and targeted delivery of the bioactive agents *(Mishra et al., 2021)*. Encapsulation plays a crucial role in preserving the biological activity and bioavailability of these compounds, making them suitable for diverse food applications. Beyond providing protection, encapsulation improves the physicochemical properties of bioactive compounds, increases their water solubility, and enables sustained release. By addressing solubility challenges, encapsulation significantly expands the potential applications of functional ingredients in food systems *(Reddy et al., 2022)*. A wide range of encapsulation technologies has been developed to encapsulate botanical bioactive compounds, differing in both the ingredients used and the processing methods employed *(Domínguez et al., 2021)*. In this section, we review some of the most significant techniques for encapsulating botanical bioactive compounds.

4.1. Emulsion solvent evaporation

This method involves two key steps: the formation of a single or double emulsion, followed by the evaporation of an organic solvent. The precipitation of the polymer, which occurs as the solvent evaporates, leads to particle formation. Solvent evaporation for microencapsulation is commonly employed in the pharmaceutical industry, particularly for controlled-release formulations. The choice of method depends on the hydrophilic or hydrophobic nature of the active molecules. For example, in simple o/w (oil-in-water) emulsification, a polymer is dissolved in a water-immiscible solvent, and the organic phase is emulsified in an aqueous phase with the help of a surfactant. However, this technique is not suitable for encapsulating highly hydrophilic agents, as it may not ensure proper encapsulation efficiency *(Lagreca et al., 2020)*.

4.2. In situ polymerization

In situ polymerization is an efficient method for producing molecularly imprinted polymers (MIPs) used in solid phase extraction (SPE) and high-performance liquid chromatography (HPLC). The reaction mixture, typically placed in a stainless-steel tube sealed at one end and subjected to ultrasonic degassing, consists of template molecules, crosslinking agents, initiators, functional monomers, and porogenic substances. Polymerization is initiated by heating the open end of the tube, allowing the process to proceed efficiently *(Kamaruzaman et al., 2021)*.

4.3. Nonoprecipitation

Nanoprecipitation, also known as solvent displacement or interfacial deposition, is a simple and reproducible method for producing submicrometer polymer-based particles. This technique typically uses biodegradable polyesters such as polylactide-co-glycolide (PLGA), poly-ε-caprolactone (PCL), and polylactide (PLA). The solvents employed in the process are water-miscible and can be removed through evaporation. The displacement of the organic solvent is facilitated by adding one phase to another under moderate magnetic agitation, leading to the interfacial deposition of the polymer *(Pulingam et al., 2022)*.

4.4. Microencapsulation

Microencapsulation is a technique used to protect food components or active ingredients from external factors such as heat, oxygen, light, moisture, and interactions with other food components, like proteins. This process involves enclosing bioactive compounds within a polymeric or non-polymeric substance, enabling their controlled release under specific conditions *(Popescu et al., 2023).*

4.5. Ionic gelation

The fundamental principle of this technique is based on the electrostatic interaction between a polymer with an opposite charge and a polyelectrolyte *(Lytle et al., 2019)*. This method offers a simple and gentle preparation process in an aqueous environment. For example, chitosan can be dissolved in acetic acid, with or without a stabilizing agent such as poloxamer or Tween 80. These stabilizers can be incorporated into the chitosan solution either before or after the addition of the polyanion. A polyanion like sodium tripolyphosphate (TPP) is then added, causing nanoparticles to spontaneously form under mechanical stirring at room temperature *(Jafernik et al., 2023)*. Figure 2 illustrates various encapsulation techniques for plant-based bioactive compounds and their applications across different industries. At the center of the diagram is a green plant, symbolizing the source of bioactive compounds. Different encapsulation methods radiate from it, each leading to a specific application.

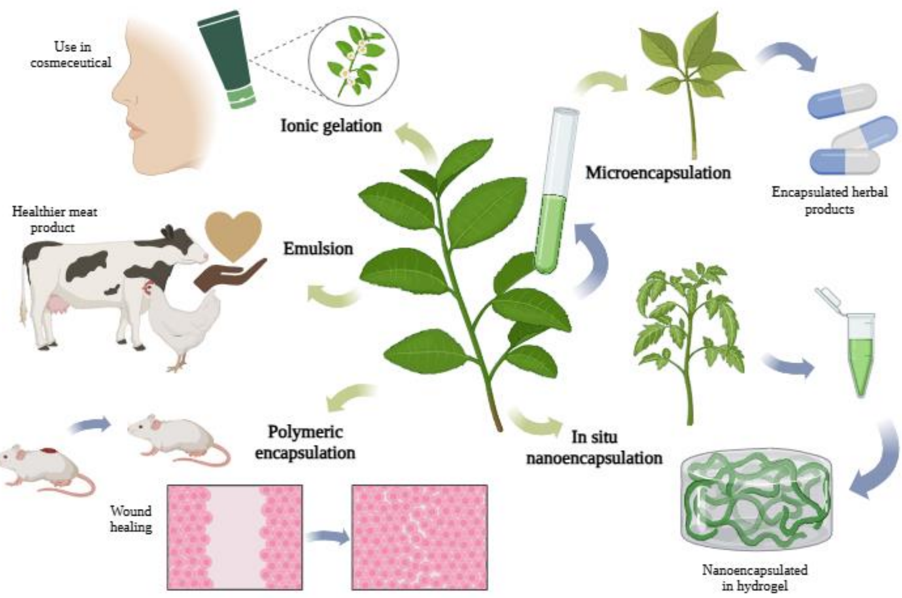

Figure 2. Encapsulation techniques for plant-based bioactive compounds and applications

Table 2 presents various methods of plant extract encapsulation in hydrogels, highlighting their diverse applications.

Table 2. Plant extracts encapsulated in hydrogels

Encapsulation method	Plant extracts	Characteristics	Application	Reference
Polymeric encapsulation	Extracts of *Eupatorium glutinosum* Lam	Excellent antioxidant Effective antibacterial activity was registered by the loaded hydrogel.	Wound healing applications in the biomedical area.	*(Zamora-Mendoza et al., 2023)*
Emulsion	*Açai* extract	The fat replacer improved burger attributes such as chewiness and firmness, while the color metric stayed unchanged during the storage duration.	Helped develop a healthier meat product that aligned with nutritional guidelines	*(Hanula et al., 2022)*
Oil-in-water emulsion and an ionic gelation	*Camellia oleifera oil*	Antioxidant activity and a porous structure	Demonstrated exceptional promise for application in the cosmeceutical industry	*(Kaolaor et al., 2024)*
Microencapsulation of hydrophilic and lipophilic compounds.	*Piper sarmentosum*	Stronger antioxidant affinity	Commercial manufacturing of encapsulated herbal products	*(Chan et al., 2010)*
***In-situ* Nanoencapsulation**	*Chamomile* extract using *Tragacanth gum* (TG)	Demonstrated good durability against washing and rubbing, coupled with controlled release behavior	Development of smart textiles for skincare.	*(Ghayempour & Montazer, 2016)*

5. Applications of hydrogels with plant extracts

Hydrogels, characterized by their three-dimensional hydrophilic polymer networks, are widely recognized for their exceptional ability to absorb and retain significant amounts of water. Their biocompatibility, flexibility, and tunable physical properties make them highly valuable in material science and diverse applications. Traditionally, chemical crosslinking agents have been utilized to stabilize these networks; however, these chemicals often introduce toxicity and pose environmental risks *(Tak et al., 2023)*. In recent years, plant extracts have emerged as promising natural alternatives. Rich in bioactive compounds—such as phenolics, flavonoids, alkaloids, and terpenoids—these extracts not only enhance the physical and chemical properties of hydrogels but also offer therapeutic benefits, including anti-inflammatory, antimicrobial, and antioxidant activities *(Skrzypczak et al., 2019)*. Furthermore, incorporating plant-based agents into hydrogels improves their mechanical strength, stability,

MJBAS PROMOTING RESEARCH & KNOWLEDGE
Mediterranean Journal of Basic and Applied Sciences (MJBAS)
Volume 9, Issue 2, Pages 180-203, April-June 2025

and controlled release of bioactive compounds, making them highly effective in various applications *(Ghayempour & Montazer, 2016)*. The encapsulation of bioactive agents within hydrogels has gained significant attention, particularly in the pharmaceutical, food, and cosmetic industries. Hydrogels are especially suited for biological encapsulation due to their water-rich environment, which supports the stability and functionality of biomolecules in biological systems.

5.1. Biomedicine and pharmacy

The integration of plant extracts into hydrogel matrices has opened new avenues in biomedicine and pharmaceutical applications. By harnessing the bioactivity of plant-derived compounds, hydrogels offer enhanced therapeutic potential while addressing the growing demand for sustainable and environmentally friendly biomedical materials. Unlike synthetic agents, plant-derived compounds are biodegradable and biocompatible, minimizing the risk of adverse reactions and promoting safer treatments. One of the most promising biomedical applications of hydrogel-plant extract combinations is in advanced wound care *(He et al., 2024)*. These hydrogel-based dressings provide a moist healing environment, stimulate cell proliferation, and accelerate tissue regeneration. In addition to wound care, hydrogels enriched with plant extracts are increasingly being utilized in drug delivery systems and tissue regeneration, thanks to their ability to control and localize the release of bioactive agents *(He et al., 2024)*.

5.2. Cosmetics

Plant extracts, rich in biologically active compounds, have been used for centuries in herbal medicine to treat skin ailments. In modern cosmetics, their incorporation into hydrogels provides an innovative solution to improve bioavailability and therapeutic effectiveness. While many plant-derived compounds suffer from limited solubility and bioavailability, hydrogel matrices address these challenges by gradually releasing the extracts, thereby enhancing their therapeutic effects *(Zagórska-Dziok et al., 2023)*. Hydrogel-infused cosmetic products can deliver a variety of phytochemicals with free radical scavenging, moisturizing, and anti-aging properties. This approach is particularly beneficial for treating skin conditions associated with inflammation, loss of elasticity, collagen degradation, and reduced hydration *(Zagórska-Dziok et al., 2023)*. Furthermore, plant extracts used in cosmetics tend to cause fewer side effects, such as irritation or allergic reactions, when compared to synthetic ingredients *(Faccio, 2020)*. The growing popularity of hydrogel materials in dermatology and cosmetology can be attributed to their efficacy in delivering active substances. These materials significantly enhance the bioavailability of phytochemicals, making them more effective for treating various skin conditions and improving overall skin health *(Zagórska-Dziok & Sobczak, 2020)*.

5.3. Food industry

Hydrogels have also found valuable applications in the food sector, particularly in the encapsulation and protection of plant extracts. By embedding herbal extracts into hydrogel matrices, their stability against external factors such as heat, light, and oxidation is significantly improved. This approach not only preserves the bioactivity of the extracts but also enhances their viability as functional food ingredients *(Fathi et al., 2022)*.

In food technology, hydrogel systems are classified into several key applications: (1) Delivery Systems, for controlled and targeted release of nutraceuticals, probiotics, and dietary supplements; (2) Packaging, acting as passive barriers to protect food from environmental factors, thereby extending shelf life by preventing contamination; (3) Coating, where edible hydrogel coatings infused with essential oils (EOs) can delay oxidation and microbial spoilage of perishable products; and (4) Texturizing Agents, which modify the texture without compromising sensory properties *(Chelu, 2024)*.

Hydrogel-based active packaging systems, combined with EOs, offer an innovative solution to extend food freshness. These packaging materials interact with the external environment to regulate temperature and humidity while preventing microbial growth. As a result, the shelf life and overall quality of food products are improved *(Carpena et al., 2021)*. Furthermore, the use of hydrogels as edible coatings, particularly those infused with EOs, is gaining attention. These coatings not only protect food products but also reduce the need for synthetic packaging materials, contributing to more sustainable food preservation methods *(Gómez-Estaca et al., 2010)*.

5.4. Agriculture

In agriculture, hydrogels infused with plant extracts present an eco-friendly alternative to chemical disinfectants and pesticides. Their biocompatibility and slow-release properties make them highly effective for delivering natural antimicrobial agents into the soil, reducing the reliance on harmful synthetic chemicals *(Valisakkagari et al., 2024)*. A recent study by Bravo Cadena and colleagues explored the use of alginate hydrogels for the controlled release of EOs extracted from cinnamon bark (*Cinnamomum zeylanicum*). These oils exhibit strong biocidal properties but are prone to rapid evaporation and degradation. By encapsulating them in hydrogels, their stability and effectiveness are significantly enhanced, making them promising candidates for sustainable agricultural practices *(Bravo Cadena et al., 2018)*.

EOs, known for their potent antimicrobial, insecticidal, and biological activities *(Ribeiro-Santos et al., 2018)*, are increasingly being recognized as viable substitutes for chemical pesticides. Their low toxicity, natural origin, and acceptance by both consumers and scientists make them attractive alternatives for environmentally friendly agricultural applications *(Bravo Cadena et al., 2018; Cofelice et al., 2021; Fierascu et al., 2020)*. Table 3 summarizes various applications of hydrogel systems enriched with plant extracts across different industries. It highlights the key benefits, bioactive compounds involved, and specific uses, showcasing the versatility and potential of these innovative materials.

Table 3. Applications and benefits of plant extract encapsulated in hydrogels.

Plant Extract	Hydrogel composition	Benefit	Reference
Lemongrass essential oil	Sodium alginate	The shelf life of bananas was extended by more than 11 days by reducing color change, weight loss, and pulp softening while preserving their physico-chemical quality and sensory attributes.	*(Iacovino et al., 2024)*

Bergenia stracheyi	Polyvinyl alcohol	Showed significant antifungal activity against *Candida albicans.* Demonstrated good biocompatibility, on human embryonic kidney (HEK) cells.	*(Tak et al., 2023)*
Calendula Officinalis, Arnica Montana	Chitosan and polyvinylpyrrolidone (PVP)	Ability to release active substances with antioxidant activity from the polymer matrix. This is indicated by the reduced pH value and confirmed by the reaction with potassium permanganate.	*(Kędzierska et al., 2024)*
S. khuzistanica ***Curcumin* and *Gymnema sylvestre***	Polyhydroxybutyrate-sodium alginate	Enhanced biocompatibility and improved cell migration promote faster healing of both normal and diabetic wounds.	*(Abazari et al., 2022)*
Tomato and potato leaf extracts with glycoalkaloids	Sodium alginate	Preliminary microbiological tests were conducted to evaluate the efficacy of the most promising biocidal formulations on model soils and in the laboratory, showing encouraging results in reducing fungal and bacterial populations.	*(Valisakkagari et al., 2024)*

The incorporation of plant extracts into hydrogel matrices offers significant potential across multiple industries. In biomedicine, they facilitate safer and more effective treatments by enhancing the bioavailability and therapeutic properties of active compounds. In cosmetics, these hydrogels improve the bioavailability and performance of skin-care products, offering benefits such as anti-aging, moisturizing, and anti-inflammatory effects. In the food sector, hydrogels enhance stability, preservation, and controlled delivery of bioactive compounds, while also contributing to sustainable packaging solutions. In agriculture, they provide an eco-friendly and efficient method for crop protection through the controlled release of natural antimicrobial agents. The versatility and sustainability of these hybrid materials make them a promising avenue for future research and industrial applications.

6. Controlled release and degradation of hydrogels

The concept of "intelligence" in materials science refers to the ability of biomaterials to dynamically respond and adapt to changes in their environment. By incorporating responsive components, these intelligent biomaterials can detect and react to factors such as light, glucose levels, ROS, and temperature variations. This adaptive capability has made them increasingly relevant in applications such as biosensors, artificial skin, medical devices, and controlled drug delivery systems *(Chakrapani et al., 2022)*. In biomedical contexts, smart biomaterials are designed to react to physical, chemical, and biological signals, allowing them to regulate physiological factors and interact with external stimuli in real time. This responsiveness makes them crucial for advancing medical solutions, particularly in chronic disease treatments and novel therapeutic strategies *(Liu et al., 2020; Tian et al., 2019)*. Advances in hydrogel framework design have led to the creation of intelligent materials—smart hydrogels—that can release their contents in a controlled manner in response to specific environmental triggers.

These smart hydrogels are capable of altering their volume and properties when exposed to external stimuli, such as pH, temperature, light, pressure, ionic force, electrical signals, and biochemical molecules (Figure 3). This adaptability enhances their value in applications like drug delivery and biosensing, where precise release control is critical for achieving optimal outcomes *(Mantha et al., 2019)*.

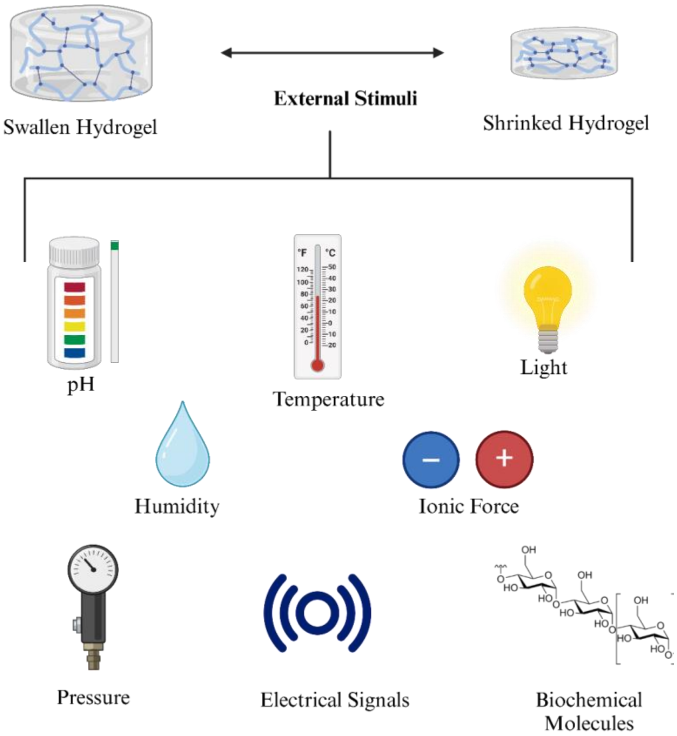

Figure 3. Interaction of smart hydrogels with external stimuli

6.1. Release kinetics of bioactive compounds

The controlled release of bioactive compounds from hydrogels is a multifaceted process governed by both intrinsic material properties and external environmental factors. Medicinal plants such as *Rosmarinus officinalis* (rosemary) are of particular interest due to their well-documented antimicrobial, antiseptic, and healing properties. The therapeutic effects of rosemary are primarily attributed to its bioactive constituents, including polyphenols (e.g., rosmarinic acid, hesperidin), diterpene and triterpene acids, and volatile oils (e.g., camphor). These compounds contribute to enhanced tissue regeneration by promoting collagen deposition, stimulating neovascularization, and reducing microbial contamination, making them promising candidates for incorporation into hydrogel-based delivery systems *(Gavan et al., 2022)*. To function effectively as carriers, hydrogels must provide both protection and a controlled release mechanism for the encapsulated agents. Release occurs through several pathways—diffusion, swelling, erosion, or degradation—often triggered by physical, chemical, or enzymatic stimuli. Key parameters influencing release kinetics include the degree of crosslinking, polymer composition, and environmental conditions. The hydrophilic nature of the polymer matrix is particularly important in modulating the diffusion behavior of bioactive compounds *(Fathi et al., 2022)*. Crosslinking density plays a pivotal role in determining the mobility of active agents within the hydrogel network. Highly crosslinked hydrogels tend to restrict diffusion, thereby prolonging the release period. Conversely, the incorporation of functional groups such as ionic moieties can establish specific interactions with the encapsulated molecules, altering their release profile. Additionally, factors like polymer molecular weight, formulation composition, and initiator concentration influence hydrogel swelling and degradation, which in turn affect the release dynamics. Smart hydrogels, equipped with stimuli-responsive architectures, offer further control by enabling site-specific and temporally regulated delivery of bioactive compounds *(Lin & Metters, 2006)*.

6.2. Biodegradability and environmental safety

Biodegradability is a critical property of hydrogels, particularly in biomedical and agriculture applications, as it ensures the material breaks down naturally and safely after fulfilling its intended function. Biodegradable hydrogels are preferred in biomedical contexts over non-degradable alternatives because they degrade under mild physiological conditions, eliminating the need for secondary removal procedures. While hydrolytically degradable hydrogels have been widely studied, there is growing interest in developing synthetic hydrogels that incorporate biological moieties capable of enzymatic degradation. This can be achieved by integrating peptide sequences that serve as substrates for enzymatic hydrolysis, enabling both the formation and degradation of the hydrogel in biological environments *(C.-C. Lin & Metters, 2006)*. Another approach involves copolymerizing naturally degradable polymers with PEG to create hybrid hydrogels. For example, PCL, which is susceptible to degradation by lipase enzymes, can be combined with PEG to form hydrogels that degrade through enzymatic action. This tailored biodegradation capability enhances the safety and biocompatibility of the material, making it suitable for various medical applications *(G. Lin et al., 2013)*.

6.3. Chitosan hydrogels: Biodegradable and antimicrobial

Chitosan, a naturally derived biopolymer obtained from the deacetylation of chitin, is non-toxic, biodegradable, and capable of undergoing enzymatic hydrolysis within the oral cavity. These properties make chitosan-based hydrogels especially well-suited for applications in oral tissue regeneration and broader biomedical fields. In addition to its degradability, chitosan possesses inherent antimicrobial activity, which further enhances its therapeutic potential by reducing the risk of infection during treatment *(Micale et al., 2020)*. When formulated as nanohydrogels, chitosan systems exhibit dynamic physicochemical behavior as they transit the gastrointestinal tract. Their structural and functional properties adapt in response to varying pH levels and enzymatic activity along the digestive pathway. Upon ingestion, nanohydrogels first encounter the acidic environment of the stomach, where they are exposed to protease and lipase enzymes that initiate partial hydrogel digestion and structural modification. As these nanohydrogels progress to the small intestine, they interact with bile salts, phospholipids, and additional digestive enzymes, which further modulate their degradation rate and size *(Fathi et al., 2022)*. This responsiveness underscores their promise in oral drug delivery and gastrointestinal therapies.

7. Trends and advances in the research of plant extracts encapsulated in hydrogels

Recent advancements in plant-based hydrogels have focused on materials derived from wood and other plant cell wall components, which offer a multiscale, abundant, and structurally organized source of nanomaterials. As water is a fundamental element of hydrogel systems, critical aspects such as water interaction, hydration, and swelling behavior are emphasized due to their central role in the design, fabrication, and performance optimization of sustainable and functional hydrogels. Notably, certain plant tissues can be regarded as natural hydrogels during specific stages of development, prompting the investigation of processes such as fluid transport, diffusion, capillarity, and ionic interactions *(Ajdary et al., 2021)*. In parallel, nanomaterials are being explored as cost-effective alternatives capable of promoting an optimal healing environment, owing to their distinctive physicochemical properties. The encapsulation of nanomaterials within hydrogels infused with plant extracts represents an emerging interdisciplinary approach that merges the advantages of nanotechnology, phytochemicals, and hydrogel systems. This strategy aims to enhance the therapeutic efficacy, stability, and controlled release of bioactive compounds, broadening the scope of biomedical applications *(Simon et al., 2022)*.

7.1. Applications of nanotechnology in plant extracts

Nanomaterials possess exceptional properties owing to their high surface-to-volume ratio, which enhances cellular interactions and contributes to improved viability and nutrient exchange in regenerated tissues. Three-dimensional nanostructured frameworks, in particular, provide an ideal environment for cell proliferation and differentiation, thereby facilitating the formation of new tissue *(Silva et al., 2023)*. Plant extracts serve as natural reducing and stabilizing agents in the synthesis of metal-based nanoparticles, including gold, silver, copper oxide, and platinum nanoparticles. These green-synthesized nanomaterials have demonstrated promising applications in biomedicine, catalysis, and environmental remediation, offering a sustainable alternative to conventional synthetic routes *(Jadoun et al., 2021)*.

The integration of nanotechnology with hydrogel systems—especially in the form of nanohydrogels—has markedly improved the delivery efficiency of natural bioactives such as medicinal plant extracts, phytochemicals, and natural antibiotics. Nanohydrogels enable the use of lower therapeutic doses, reduce potential side effects, and enhance bioavailability. Moreover, they improve the solubility of hydrophobic natural compounds, thereby broadening their pharmaceutical applicability and maximizing the therapeutic potential of these abundant biological resources *(Lestari et al., 2023)*. Nanotechnology has thus revolutionized the utilization of plant-derived compounds by significantly enhancing their stability, bioavailability, and therapeutic performance. Some of the key applications of plant extract-based nanohydrogel systems include:

7.1.1. Biomedical applications

Nanotechnology has significantly advanced biomedical research by offering innovative solutions for disease treatment, diagnostics, and tissue regeneration. In this context, plant-based nanotechnology has emerged as a sustainable and eco-friendly alternative, reducing environmental impact while enhancing therapeutic efficacy. A notable example is the development of Aloe vera-based nanoparticles, which exhibit strong wound-healing properties. When combined with epidermal growth factors (EGF), these nanoparticles promote cell proliferation, migration, and angiogenesis, markedly accelerating the healing of chronic wounds in animal models *(Karnwal et al., 2024)*. Plant-derived nanocarriers—such as liposomes, nanoemulsions, and nanohydrogels—have been widely explored for the encapsulation of bioactive compounds. These systems enable precise targeting and controlled release of plant extracts, improving pharmacokinetics and minimizing adverse effects *(Chavda et al., 2022)*. Additionally, the convergence of nanotechnology with flavonoid research has introduced novel strategies to stabilize and deliver these potent natural antioxidants. Flavonoids, abundant in fruits and vegetables, are known for their cardiovascular benefits, and their nanoformulations offer enhanced bioavailability and therapeutic performance *(Abdi Syahputra et al., 2024)*.

7.1.2. Environmental applications

Encapsulation of plant extracts in hydrogels has garnered significant attention in environmental science due to its capacity to enhance the stability, control the release, and improve the efficacy of bioactive compounds. Several studies have highlighted the potential of these systems for sustainable applications. For instance, *Clemente et al.* (2023) reported the development of hydrogel beads loaded with plant extracts from the Solanaceae family, demonstrating their effectiveness in removing water contaminants *(Clemente et al., 2023)*. Ajdary et al. (2021) explored the design of multifunctional hydrogels inspired by natural materials, underscoring their adaptability for use in engineering, agriculture, and environmental remediation *(Ajdary et al., 2021)*. Furthermore, Ghayempour and Montazer (2016) developed a durable cotton fabric via nanoencapsulation of chamomile extract using TG as the encapsulating matrix. This approach, involving an eco-friendly binder with hydrogel-like properties, enabled controlled release and enhanced textile functionality. Their study compared different application methods for herbal product encapsulation, demonstrating improved material performance *(Ghayempour & Montazer, 2016)*.

8. Conclusion

Plant extract-encapsulated hydrogels represent a promising and sustainable technology with broad applicability in biomedicine, cosmetics, food, and agriculture. Their inherent ability to retain water, control the release of bioactive compounds, and enhance stability makes them particularly effective for controlled drug delivery, wound healing, and preservation systems. Recent advancements in encapsulation techniques and nanotechnology have significantly improved the bioavailability, therapeutic efficacy, and targeted delivery of plant-derived molecules. As research progresses, the integration of nanomaterials within hydrogel matrices is expected to foster innovations in sustainable healthcare, environmental remediation, and eco-friendly agricultural practices. This evolving field underscores the potential of hydrogels as environmentally responsible, multifunctional platforms for future technological developments.

9. Future Suggestions

The following are the future suggestions.

(i) Expanding the use of hybrid hydrogel systems that synergize the advantages of natural polymers (biocompatibility and biodegradability) with those of synthetic ones (mechanical strength, customizable functionality).

(ii) Exploring green synthesis approaches and fully biodegradable matrices to minimize the environmental footprint of hydrogel production.

(iii) Conducting high-throughput screening of plant polymer combinations supporting by computational modeling.

(iv) Synergistic bioactive formulations combining multiple types of plant-derived compounds (antioxidants and anti-inflammatories).

(v) Agricultural applications and environmental monitoring, the use of bioactive-loaded hydrogels as controlled released platforms.

Declarations

Source of Funding

This research did not benefit from grant from any non-profit, public or commercial funding agency.

Competing Interests Statement

The authors have declared that no competing financial, professional or personal interests exist.

Consent for publication

All the authors contributed to the manuscript and consented to the publication of this research work.

Authors' contributions

All the authors took part in literature review, analysis, and manuscript writing equally.

Availability of data and materials

Authors are willing to share data and material according to the relevant needs.

Acknowledgments

María I. León-Campos gratefully acknowledges the Secretaría de Ciencia, Humanidades, Tecnología e Innovación (SECIHTI) for the doctoral scholarship support.

References

Abazari, M., Akbari, T., Hasani, M., Sharifikolouei, E., Raoufi, M., Foroumadi, A., Sharifzadeh, M., Firoozpour, L., & Khoobi, M. (2022). Polysaccharide-based hydrogels containing herbal extracts for wound healing applications. Carbohydrate Polymers, 294: 119808. https://doi.org/10.1016/j.carbpol.2022.119808.

Abdi Syahputra, R., Dalimunthe, A., Utari, Z.D., Halim, P., Sukarno, M.A., Zainalabidin, S., Salim, E., Gunawan, M., Nurkolis, F., Park, M.N., Luckanagul, J.A., Bangun, H., Kim, B., & Harahap, U. (2024). Nanotechnology and flavonoids: Current research and future perspectives on cardiovascular health. Journal of Functional Foods, 120: 106355. https://doi.org/10.1016/j.jff.2024.106355.

Ajdary, R., Tardy, B.L., Mattos, B.D., Bai, L., & Rojas, O.J. (2021). Plant Nanomaterials and Inspiration from Nature: Water Interactions and Hierarchically Structured Hydrogels. Advanced Materials, 33(28): 894. https://doi.org/10.1002/adma.202001085.

Ali, K., Asad, Z., Agbna, G.H.D., Saud, A., Khan, A., & Zaidi, S.J. (2024). Progress and Innovations in Hydrogels for Sustainable Agriculture. Agronomy, 14(12): 2815. https://doi.org/10.3390/agronomy14122815.

Armendáriz-Barragán, B., Zafar, N., Badri, W., Galindo-Rodríguez, S.A., Kabbaj, D., Fessi, H., & Elaissari, A. (2016). Plant extracts: from encapsulation to application. Expert Opinion on Drug Delivery, 13(8): 1165–1175. https://doi.org/10.1080/17425247.2016.1182487.

Azeera, M., Vaidevi, S., & Ruckmani, K. (2019). Characterization Techniques of Hydrogel and Its Applications. 56: 737–761. https://doi.org/10.1007/978-3-319-77830-3_25.

Bravo Cadena, M., Preston, G.M., Van der Hoorn, R.A.L., Flanagan, N.A., Townley, H.E., & Thompson, I.P. (2018). Enhancing cinnamon essential oil activity by nanoparticle encapsulation to control seed pathogens. Industrial Crops and Products, 124: 755–764. https://doi.org/10.1016/j.indcrop.2018.08.043.

Carpena, M., Nuñez-Estevez, B., Soria-López, A., García-Oliveira, P., & Prieto, M.A. (2021). Essential Oils and Their Application on Active Packaging Systems: A Review. Resources, 10(1): 7. https://doi.org/10.3390/resources 10010007.

Chakrapani, G., Zare, M., & Ramakrishna, S. (2022). Intelligent hydrogels and their biomedical applications. Materials Advances, 3(21): 7757–7772. https://doi.org/10.1039/d2ma00527a.

Chan, E.S., Yim, Z.H., Phan, S.H., Mansa, R.F., & Ravindra, P. (2010). Encapsulation of herbal aqueous extract through absorption with ca-alginate hydrogel beads. Food and Bioproducts Processing, 88(2–3): 195–201. https://doi.org/10.1016/j.fbp.2009.09.005.

Chavda, V.P., Patel, A.B., Mistry, K.J., Suthar, S.F., Wu, Z.X., Chen, Z.S., & Hou, K. (2022). Nano-Drug Delivery Systems Entrapping Natural Bioactive Compounds for Cancer: Recent Progress and Future Challenges. Frontiers in Oncology, 12: 346. https://doi.org/10.3389/fonc.2022.867655.

Chelu, M. (2024). Hydrogels with Essential Oils: Recent Advances in Designs and Applications. Gels, 10(10): 636. https://doi.org/10.3390/gels10100636.

Choi, H., Choi, W.S., & Jeong, J.O. (2024). A Review of Advanced Hydrogel Applications for Tissue Engineering and Drug Delivery Systems as Biomaterials. Gels, 10(11): 693. https://doi.org/10.3390/gels10110693.

Clemente, I., Baglioni, M., Bonechi, C., Bisozzi, F., Rossi, C., & Tamasi, G. (2023). Green Hydrogels Loaded with Extracts from Solanaceae for the Controlled Disinfection of Agricultural Soils. Polymers, 15(22): 4455. https://doi.org/10.3390/polym15224455.

Cofelice, M., Cinelli, G., López, F., Di Renzo, T., Coppola, R., & Reale, A. (2021). Alginate-Assisted Lemongrass (*Cymbopogon nardus*) Essential Oil Dispersions for Antifungal Activity. Foods, 10(7): 1528. https://doi.org/10.3390/foods10071528.

Delgado-Pujol, E.J., Martínez, G., Casado-Jurado, D., Vázquez, J., León-Barberena, J., Rodríguez-Lucena, D., Torres, Y., Alcudia, A., & Begines, B. (2025). Hydrogels and Nanogels: Pioneering the Future of Advanced Drug Delivery Systems. Pharmaceutics, 17(2): 215. https://doi.org/10.3390/pharmaceutics17020215.

Domínguez, R., Pateiro, M., Munekata, P.E.S., McClements, D.J., & Lorenzo, J.M. (2021). Encapsulation of Bioactive Phytochemicals in Plant-Based Matrices and Application as Additives in Meat and Meat Products. Molecules, 26(13): 3984. https://doi.org/10.3390/molecules26133984.

Dubourg, G., Elsawi, Z., & Raoult, D. (2015). Assessment of the in vitro antimicrobial activity of Lactobacillus species for identifying new potential antibiotics. International Journal of Antimicrobial Agents, 46(5): 590–593. https://doi.org/10.1016/j.ijantimicag.2015.05.011.

Faccio, G. (2020). Plant Complexity and Cosmetic Innovation. IScience, 23(8): 101358. https://doi.org/10.1016/j.isci.2020.101358.

Fang, X., Wang, J., Ye, C., Lin, J., Ran, J., Jia, Z., Gong, J., Zhang, Y., Xiang, J., Lu, X., Xie, C., & Liu, J. (2024). Polyphenol-mediated redox-active hydrogel with H_2S gaseous-bioelectric coupling for periodontal bone healing in diabetes. Nature Communications, 15(1): 9071. https://doi.org/10.1038/s41467-024-53290-6.

Fathi, M., Ahmadi, N., Forouhar, A., & Hamzeh Atani, S. (2022). Natural Hydrogels, the Interesting Carriers for Herbal Extracts. Food Reviews International, 38(s): 713–737. https://doi.org/10.1080/87559129.2021.1885436.

Fierascu, R.C., Fierascu, I.C., Dinu-Pirvu, C.E., Fierascu, I., & Paunescu, A. (2020). The application of essential oils as a next-generation of pesticides: recent developments and future perspectives. Zeitschrift Für Naturforschung C., 75(7–8): 183–204. https://doi.org/10.1515/znc-2019-0160.

Gavan, A., Colobatiu, L., Hanganu, D., et al. (2022). Development and Evaluation of Hydrogel Wound Dressings Loaded with Herbal Extracts. Processes, 10(2): 242. https://doi.org/10.3390/pr10020242.

Ghayempour, S., & Montazer, M. (2016). A robust friendly nano-encapsulated plant extract in hydrogel Tragacanth gum on cotton fabric through one single step in-situ synthesis and fabrication. Cellulose, 23(4): 2561–2572. https://doi.org/10.1007/s10570-016-0958-2.

Gómez-Estaca, J., López de Lacey, A., López-Caballero, M.E., Gómez-Guillén, M.C., & Montero, P. (2010). Biodegradable gelatin–chitosan films incorporated with essential oils as antimicrobial agents for fish preservation. Food Microbiology, 27(7): 889–896. https://doi.org/10.1016/j.fm.2010.05.012.

Hanula, M., Szpicer, A., Górska-Horczyczak, E., Khachatryan, G., Pogorzelski, G., Pogorzelska-Nowicka, E., & Poltorak, A. (2022). Hydrogel Emulsion with Encapsulated Safflower Oil Enriched with Açai Extract as a Novel Fat Substitute in Beef Burgers Subjected to Storage in Cold Conditions. Molecules, 27(8): 2397. https://doi.org/10.3390/molecules27082397.

He, X., Gao, S., Li, H., Liu, H., Zhao, S., Wang, H., Qin, S., Li, J., Zhou, F., & Xie, J. (2024). Hybrid hydrogel loaded with natural plant extract accelerates diabetic wound healing via ROS scavenging and immunoregulation. Chemical Engineering Journal, 499: 156388. https://doi.org/10.1016/j.cej.2024.156388.

Ho, T.C., Chang, C.C., Chan, H.P., Chung, T.W., Shu, C.W., Chuang, K.P., Duh, T.H., Yang, M.H., & Tyan, Y.C. (2022). Hydrogels: Properties and Applications in Biomedicine. Molecules, 27(9): 2902. https://doi.org/10.3390/molecules27092902.

Huynh, N., Valle-Delgado, J.J., Fang, W., Arola, S., & Österberg, M. (2023). Tuning the water interactions of cellulose nanofibril hydrogels using willow bark extract. Carbohydrate Polymers, 317: 121095. https://doi.org/10.1016/j.carbpol.2023.121095.

Iacovino, S., Cofelice, M., Sorrentino, E., Cuomo, F., Messia, M.C., & Lopez, F. (2024). Alginate-Based Emulsions and Hydrogels for Extending the Shelf Life of Banana Fruit. Gels, 10(4): 245. https://doi.org/10.3390/gels10040245.

Iqbal, U., Malik, A., Sial, N.T., Mehmood, M.H., Uttra, A.M., Tulain, U.R., Erum, A., Fayyaz-ur-Rehman, M., Welson, N.N., Mahmoud, M.H., Alexiou, A., Papadakis, M., & El-Saber Bathia, G. (2025). Eucalyptol attenuates indomethacin-induced gastric ulcers in rats by modulating the ICAM-1, eNOS and COX/LOX pathways: Insights from in silico, in vitro and in vivo approaches. Food and Chemical Toxicology, 199: 115319. https://doi.org/10.1016/j.fct.2025.115319.

Jadoun, S., Arif, R., Jangid, N.K., & Meena, R.K. (2021). Green synthesis of nanoparticles using plant extracts: a review. Environmental Chemistry Letters, 19(1): 355–374. https://doi.org/10.1007/s10311-020-01074-x.

Jafernik, K., Ładniak, A., Blicharska, E., Czarnek, K., Ekiert, H., Wiącek, A.E., & Szopa, A. (2023). Chitosan-Based Nanoparticles as Effective Drug Delivery Systems—A review. Molecules, 28(4): 1963. https://doi.org/10.3390/molecules28041963.

Kaith, B.S., Singh, A., Sharma, A.K., & Sud, D. (2021). Hydrogels: Synthesis, Classification, Properties and Potential Applications—A Brief Review. Journal of Polymers and the Environment, 29(12): 3827–3841. https://doi.org/10.1007/s10924-021-02184-5.

Kamaruzaman, S., Nasir, N.M., Mohd Faudzi, S.M., Yahaya, N., Mohamad Hanapi, N. S., & Wan Ibrahim, W.N. (2021). Solid-Phase Extraction of Active Compounds from Natural Products by Molecularly Imprinted Polymers: Synthesis and Extraction Parameters. Polymers, 13(21): 780. https://doi.org/10.3390/polym13213780.

Kaolaor, A., Kiti, K., Pankongadisak, P., & Suwantong, O. (2024). *Camellia oleifera* oil-loaded chitosan nanoparticles embedded in hydrogels as cosmeceutical products with improved biological properties and sustained drug release. International Journal of Biological Macromolecules, 275: 133560. https://doi.org/10.1016/j.ijbiomac.2024.133560.

Karnwal, A., Jassim, A.Y., Mohammed, A.A., Sharma, V., Al-Tawaha, A. R. M. S., & Sivanesan, I. (2024). Nanotechnology for Healthcare: Plant-Derived Nanoparticles in Disease Treatment and Regenerative Medicine. Pharmaceuticals, 17(12): 1711. https://doi.org/10.3390/ph17121711.

Kaur, H., Gogoi, B., Sharma, I., Das, D.K., Azad, M.A., Pramanik, D.D., & Pramanik, A. (2024). Hydrogels as a Potential Biomaterial for Multimodal Therapeutic Applications. Molecular Pharmaceutics, 21(10): 4827–4848. https://doi.org/10.1021/acs.molpharmaceut.4c00595.

Kawee-ai, A. (2025). Advancing Gel Systems with Natural Extracts: Antioxidant, Antimicrobial Applications, and Sustainable Innovations. Gels, 11(2): 125. https://doi.org/10.3390/gels11020125.

Kędzierska, M., Sala, K., Bańkosz, M., Grzela, K., Potemski, P., Miernik, K., & Tyliszczak, B. (2024). Enhanced Hydrogel Materials: Incorporating Vitamin C and Plant Extracts for Biomedical Applications. Molecules, 29(11): 2633. https://doi.org/10.3390/molecules29112633.

Kędzierska, M., Sala, K., Bańkosz, M., Wroniak, D., Gajda, P., Potemski, P., & Tyliszczak, B. (2023). Investigation of Physicochemical Properties and Surface Morphology of Hydrogel Materials Incorporating Rosehip Extract. Materials, 16(17): 6037. https://doi.org/10.3390/ma16176037.

Khan, M.U.A., Aslam, M.A., Abdullah, M.F. Bin, Al-Arjan, W.S., Stojanovic, G.M., & Hasan, A. (2024). Hydrogels: Classifications, fundamental properties, applications, and scopes in recent advances in tissue engineering and regenerative medicine – A comprehensive review. Arabian Journal of Chemistry, 17(10): 105968. https://doi.org/10.1016/j.arabjc.2024.105968.

Kudasova, D., Mutaliyeva, B., Vlahoviček-Kahlina, K., Jurić, S., Marijan, M., Khalus, S.V., Prosyanik, A.V., Šegota, S., Španić, N., & Vinceković, M. (2021). Encapsulation of Synthesized Plant Growth Regulator Based on Copper(II) Complex in Chitosan/Alginate Microcapsules. International Journal of Molecular Sciences, 22(5): 2663. https://doi.org/10.3390/ijms22052663.

Kusjuriansah, K., Rodhiyah, M., Syifa, N.A., Luthfianti, H.R., Waresindo, W.X., Hapidin, D.A., Suciati, T., Edikresnha, D., & Khairurrijal, K. (2024). Composite Hydrogel of Poly(vinyl alcohol) Loaded by *Citrus hystrix* Leaf Extract, Chitosan, and Sodium Alginate with In Vitro Antibacterial and Release Test. ACS Omega, 56: 23–134. https://doi.org/10.1021/acsomega.3c10143.

Lagreca, E., Onesto, V., Di Natale, C., La Manna, S., Netti, P.A., & Vecchione, R. (2020). Recent advances in the formulation of PLGA microparticles for controlled drug delivery. Progress in Biomaterials, 9(4): 153–174. https://doi.org/10.1007/s40204-020-00139-y.

Lestari, U., Muhaimin, M., Chaerunisaa, A.Y., & Sujarwo, W. (2023). Improved Solubility and Activity of Natural Product in Nanohydrogel. Pharmaceuticals, 16(12): 1701. https://doi.org/10.3390/ph16121701.

Leyva-Jiménez, F.J., Oliver-Simancas, R., Castangia, I., Rodríguez-García, A.M., & Alañón, M.E. (2023). Comprehensive review of natural based hydrogels as an upcoming trend for food packing. Food Hydrocolloids, 135: 108124. https://doi.org/10.1016/j.foodhyd.2022.108124.

Li, Z., Chen, Z., Chen, H., Chen, K., Tao, W., Ouyang, X., Mei, L., & Zeng, X. (2022). Polyphenol-based hydrogels: Pyramid evolution from crosslinked structures to biomedical applications and the reverse design. Bioactive Materials, 17: 49–70. https://doi.org/10.1016/j.bioactmat.2022.01.038.

Lin, C.C., & Metters, A.T. (2006). Hydrogels in controlled release formulations: Network design and mathematical modeling. Advanced Drug Delivery Reviews, 58(12–13): 1379–1408. https://doi.org/10.1016/j.addr.2006.09.004.

Lin, G., Cosimbescu, L., Karin, N.J., Gutowska, A., & Tarasevich, B.J. (2013). Injectable and thermogelling hydrogels of PCL-g-PEG: mechanisms, rheological and enzymatic degradation properties. Journal of Materials Chemistry B., 1(9): 1249. https://doi.org/10.1039/c2tb00468b.

Lin, Y.Y., Lu, S.H., Gao, R., Kuo, C.H., Chung, W.H., Lien, W.C., Wu, C.C., Diao, Y., & Wang, H.M. D. (2021). A Novel Biocompatible Herbal Extract-Loaded Hydrogel for Acne Treatment and Repair. Oxidative Medicine and Cellular Longevity, 20(1): 91 https://doi.org/10.1155/2021/5598291.

Liu, K., Tebyetekerwa, M., Ji, D., & Ramakrishna, S. (2020). Intelligent Materials. Matter, 3(3): 590–593. https://doi.org/10.1016/j.matt.2020.07.003.

Lytle, T.K., Chang, L.W., Markiewicz, N., Perry, S.L., & Sing, C.E. (2019). Designing Electrostatic Interactions via Polyelectrolyte Monomer Sequence. ACS Central Science, 5(4): 709–718. https://doi.org/10.1021/acscentsci.9b00087.

Mantha, S., Pillai, S., Khayambashi, P., Upadhyay, A., Zhang, Y., Tao, O., Pham, H.M., & Tran, S.D. (2019). Smart Hydrogels in Tissue Engineering and Regenerative Medicine. Materials, 12(20): 3323. https://doi.org/10.3390/ma12203323.

Micale, N., Citarella, A., Molonia, M.S., et al. (2020). Hydrogels for the Delivery of Plant-Derived (Poly)Phenols. Molecules, 25(14): 3254. https://doi.org/10.3390/molecules25143254.

Mishra, S., Sahani, S., Arvind, & Pal, V. (2021). Encapsulation of Herbal Extracts. Pages 115–133. https://doi.org/10.1007/978-3-030-76813-3_5.

Nisa, R.U., Nisa, A.U., Tantray, A.Y., Shah, A.H., Jan, A.T., Shah, A.A., & Wani, I.A. (2024). Plant phenolics with promising therapeutic applications against skin disorders: A mechanistic review. Journal of Agriculture and Food Research, 16: 101090. https://doi.org/10.1016/j.jafr.2024.101090.

Popescu, L., Cojocari, D., Ghendov-Mosanu, A., Lung, I., Soran, M.L., Opriş, O., Kacso, I., Ciorîţă, A., Balan, G., Pintea, A., & Sturza, R. (2023). The Effect of Aromatic Plant Extracts Encapsulated in Alginate on the Bioactivity, Textural Characteristics and Shelf Life of Yogurt. Antioxidants, 12(4): 893. https://doi.org/10.3390/antiox12040893.

Pulingam, T., et al. (2022). Exploring Various Techniques for the Chemical and Biological Synthesis of Polymeric Nanoparticles. Nanomaterials, 12(3): 576. https://doi.org/10.3390/nano12030576.

Rahmawati, S.I., Indriani, D.W., Ningsih, F.N., Hardhiyuna, M., Firdayani, F., Ahmadi, P., Rosyidah, A., Septiana, E., Dharmayanti, N.L.P.I., Bayu, A., & Putra, M.Y. (2024). Dual anti-inflammatory activities of COX-2/5-LOX driven by kratom alkaloid extracts in lipopolysaccharide-induced RAW 264.7 cells. Scientific Reports, 14(1): 28993. https://doi.org/10.1038/s41598-024-79229-x.

Ramírez-Brewer, D., Quintana-Martínez, S.E., & García-Zapateiro, L.A. (2025). Obtaining and characterization of natural extracts from mango (*Mangifera Indica*) peel and its effect on the rheological behavior in new mango kernel starch hydrogels. Food Chemistry, 462: 140949. https://doi.org/10.1016/j.foodchem.2024.140949.

Reddy, C.K., Agarwal, R.K., Shah, M.A., & Suriya, M. (2022). Encapsulation techniques for plant extracts. In Plant Extracts: Applications in the Food Industry, Pages 75–88, Elsevier. https://doi.org/10.1016/b978-0-12-822475-5.00008-9.

Ribeiro-Santos, R., Andrade, M., Sanches-Silva, A., & de Melo, N.R. (2018). Essential Oils for Food Application: Natural Substances with Established Biological Activities. Food and Bioprocess Technology, 11(1): 43–71. https://doi.org/10.1007/s11947-017-1948-6.

Sampedro-Guerrero, J., Vives-Peris, V., Gomez-Cadenas, A., & Clausell-Terol, C. (2023). Efficient strategies for controlled release of nanoencapsulated phytohormones to improve plant stress tolerance. Plant Methods, 19(1): 47. https://doi.org/10.1186/s13007-023-01025-x.

Sarkar, S., & Levi-Polyachenko, N. (2020). Conjugated polymer nano-systems for hyperthermia, imaging and drug delivery. Advanced Drug Delivery Reviews, 163–164: 40–64. https://doi.org/10.1016/j.addr.2020.01.002.

Silva, D.F., Melo, A.L.P., Uchôa, A.F.C., Pereira, G.M.A., Alves, A.E.F., Vasconcellos, M.C., Xavier-Júnior, F.H., & Passos, M.F. (2023). Biomedical Approach of Nanotechnology and Biological Risks: A Mini-Review. International Journal of Molecular Sciences, 24(23): 16719. https://doi.org/10.3390/ijms242316719.

Simon, S., Sibuyi, N.R.S., Fadaka, A.O., Meyer, S., Josephs, J., Onani, M.O., Meyer, M., & Madiehe, A.M. (2022). Biomedical Applications of Plant Extract-Synthesized Silver Nanoparticles. Biomedicines, 10(11): 2792. https://doi.org/10.3390/biomedicines10112792.

Skrzypczak, D., Mikula, K., & Witek-Krowiak, A. (2019). Hydrogel capsules with alfalfa as micronutrients carrier. SN Applied Sciences, 1(6): 573. https://doi.org/10.1007/s42452-019-0575-4.

Song, X., Guo, J., Liu, Y., Li, F., Yang, Q., Guan, F., & Di, C. (2022). Preparation and characterization of multi-network hydrogels based on sodium alginate/krill protein/polyacrylamide—Strength, shape memory, conductivity and biocompatibility. International Journal of Biological Macromolecules, 207: 140–151. https://doi.org/10.1016/j.ijbiomac.2022.03.015.

Tak, U.N., Rashid, S., Ahangar, F.A., Kour, P., Shaheen, A., Sidiq, S., Gousia, Manhas, A.A., Nazir, N., & Dar, A.A. (2023). A composite polyvinyl alcohol–medicinal plant extract crosslinked hydrogel: a novel soft system with excellent rhodamine B adsorption and significant antifungal activity. New Journal of Chemistry, 47(28): 13422–13435. https://doi.org/10.1039/d3nj02229c.

Tian, S., Yang, W., Grange, J.M. Le, Wang, P., Huang, W., & Ye, Z. (2019). Smart healthcare: making medical care more intelligent. Global Health Journal, 3(3): 62–65. https://doi.org/10.1016/j.glohj.2019.07.001.

Valisakkagari, H., Chaturvedi, C., & Rupasinghe, H.P.V. (2024). Green Extraction of Phytochemicals from Fresh Vegetable Waste and Their Potential Application as Cosmeceuticals for Skin Health. Processes, 12(4): 742. https://doi.org/10.3390/pr12040742.

Zagórska, D.M., & Sobczak, M. (2020). Hydrogel-Based Active Substance Release Systems for Cosmetology and Dermatology Application: A Review. Pharma., 12(5): 396. https://doi.org/10.3390/pharmaceutics12050396.

Zagórska-Dziok, M., Ziemlewska, A., Mokrzyńska, A., Nizioł-Łukaszewska, Z., Wójciak, M., & Sowa, I. (2023). Evaluation of the Biological Activity of Hydrogel with *Cornus mas* L. Extract and Its Potential Use in Dermatology and Cosmetology. Molecules, 28(21): 7384. https://doi.org/10.3390/molecules28217384.

Zamora-Mendoza, L., Vispo, S.N., De Lima, L., Mora, J.R., Machado, A., & Alexis, F. (2023). Hydrogel for the Controlled Delivery of Bioactive Components from Extracts of *Eupatorium glutinosum* Lam. Leaves. Molecules, 28(4): 1591. https://doi.org/10.3390/molecules28041591.

Zeng, Q., Xiao, W., Zhang, H., Liu, W., Wang, X., Li, Z., Han, Y., Wang, Z., Li, S., Yang, J., & Ouyang, W. (2025). α-spinasterol isolated from *Achyranthes aspera* L. ameliorates inflammation via NF-κB and Nrf2/HO-1 pathways. Scientific Reports, 15(1): 5723. https://doi.org/10.1038/s41598-025-90022-2.

Zhao, Z.L., Peng, D., Liu, X., Li, X.C., Lan, L.J., Wu, X.H., Liu, X.A., Cui, J.H., Lee, B.J., Shi, L.L., & Cao, Q.R. (2023). Formulation and characterization of tadalafil-loaded orodispersible films with enhanced dissolution rate and membrane permeability. Journal of Drug Delivery Science and Technology, 84: 104535. https://doi.org/10.1016/j.jddst.2023.104535.

Zulkefli, N., Che Zahari, C.N.M., Sayuti, N.H., Kamarudin, A.A., Saad, N., Hamezah, H.S., Bunawan, H., Baharum, S.N., Mediani, A., Ahmed, Q.U., Ismail, A.F.H., & Sarian, M.N. (2023). Flavonoids as Potential Wound-Healing Molecules: Emphasis on Pathways Perspective. International Journal of Molecular Sciences, 24(5): 4607. https://doi.org/10.3390/ijms24054607.