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Valorization of Food By-Products for Bio-Based Hydrogel Development: A Circular Approach on Bromelain Encapsulation Case Study

Ana Martins Vilas-Boas, Débora A. Campos, and Maria Manuela Pintado 

Escola Superior de Biotecnologia, CBQF—Centro de Biotecnologia e Química Fina—Laboratório Associado, Universidade Católica Portuguesa, Porto, Portugal

ABSTRACT

Food by-product valorization is rapidly gaining importance as a sustainable strategy for designing bio-based hydrogels. This review adopts bromelain, a proteolytic enzyme from pineapple side-streams, as a central case study, offering a targeted perspective rarely explored in the literature. Through a comparative analysis of natural hydrogel matrices derived from food waste, we assess how gelation mechanisms, enzyme – matrix compatibility and barrier properties impact bromelain’s stability, bioactivity and release performance. This work integrates insights with translation-oriented considerations, including scalability, techno-economic and life-cycle assessment, regulatory compliance and supply-chain readiness. By mapping bromelain encapsulation strategies onto a circular bioeconomy framework, we demonstrate how food-waste-derived hydrogels can simultaneously advance enzyme delivery technologies and promote zero-waste solutions. The findings highlight both the opportunities and the critical gaps, particularly in reproducibility, regulatory alignment and industrial scale-up. Bromelain case studies further underline the enzyme’s growing interest for drug delivery, wound healing and nutraceutical applications, clarifying when waste-derived hydrogels outperform conventional systems. This review delivers a unique contribution by merging scientific advances with a practical decision framework, offering guidance on selecting matrices and crosslinkers tailored to bromelain’s activity profile, positioning food-waste-based hydrogels not merely as experimental materials but as credible, future-ready platforms for nutraceutical and biomedical innovation.

KEYWORDS

Bromelain; Circular economy; Food waste; Food by-products; Hydrogels

Introduction

The increasing global demand for food and food products has continuously grown over the years as the human population increases, generating high levels of food waste throughout the food supply chain from production to end-users. Food waste (FW) represents one-third of the total food produced per year with approximately 1.3 billion tons of waste production and is expected to grow in the next 25 years, representing US \$2.6 trillion of global food costs annually, of which US \$1 trillion of economic loss, US \$700 billion of environmental costs and US \$900 billion of social costs.^[1–4] Developed countries account for most of this waste, with North America and Europe representing 280–300 kg of FW per person. Approximately 45% of total fruit and vegetable production is wasted throughout the food chain, from the field to consumption, and in this waste several compounds of high potential, such as proteins, lipids, fibers, carbohydrates, polyphenols and other bioactive compounds, are disregarded.^[1]

CONTACT Maria Manuela Pintado  mpintado@porto.ucp.pt  Escola Superior de Biotecnologia, CBQF—Centro de Biotecnologia e Química Fina—Laboratório Associado, Universidade Católica Portuguesa, Rua Diogo Botelho, Porto 1327, Portugal

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Building on the potential of food by-product valorization to minimize waste and enhance sustainability, hydrogels derived from bioactive compounds extracted from these by-products offer a compelling solution for nutraceutical applications. This review article provides a critical up-to-date literature overview on hydrogels obtained from added-value molecules extracted from food byproducts touching in particular its nutraceutical applications, allowing the promotion of a circular bioeconomy approach in the agrifood system.

The importance of food by-products to reduce food waste

FW is generated during processing, distribution, selling, consumption and post consumption phases. At the processing stage FW production occurs usually due to mechanical damage or spilling at harvesting, prepping stages, storage conditions, environmental factors like changes in climate, financial concerns like policies, and consumer principles like qualitative characteristics and appearance. The distribution stage can cause inappropriate transportation, unsuitable packaging, time restraints and poor logistics. At the retailer stage can occur mishandling, climatic conditions changes, unsuitable packaging, expiration and strict food guidelines. Concerning consumption stage FW can occur during shopping, absence of awareness of food utilization, expiration and packaging. In Europe, most of the food waste production happens on the production (23%), handling/storage (11%) and consumption (52%) stages, accounting for 88 million tons of FW per year.^[5,6] The food supply chain is estimated to produce around 30% of FW, which can sufficiently provide food for 1 billion people.^[5,7] The United Nations Sustainable Development Goals target the reduction of food losses through the food supply chain by 2030, and Europe aims to decrease 30% of FW by 2025.^[6,8]

The increasing waste generation brings concerns regarding fruit and vegetable losses, global hunger, environmental pollution, food security and socio-economic factors triggering researchers into studying and developing new innovative mechanisms for tackling the FW problem.^[1]

The circular bioeconomy merges closed-loop systems with the conversion of organic waste, agricultural, and forest biomass into biomaterials and biochemicals through biorefining. This closed-loop framework adopts the cradle-to-cradle philosophy, emphasizing endless recycling or environmentally harmless disposal of waste.^[6] The concept is a noteworthy strategy for decreasing food waste and associated problems, as its primary goal is to reduce environmental, societal and economic impacts transforming renewable biological sources into high-value products like bioactive compounds, biomaterials and biofuels, maintaining the resource value and aiming for zero-waste approaches and reduced greenhouse gases emissions.^[1] The production of animal feed, biomaterials, biofuels and other high-value products such as enzymes, organic acids, biopolymers, polyphenols and compost utilizing natural wasted resources, like peelings, cores, flesh, trimmings, etc., brings economic gains and, parallelly, addresses environmental concerns.^[1]

The abovementioned recoverable compounds offer enormous opportunities to several industries like nutraceutical, pharmaceutical, textile, cosmetic, etc. to produce and apply natural substitutes to synthetic compounds, with a multitude of interesting characteristics. For example, bioactive compounds and biomaterials have been reported to provide extra-nutritious and health benefits that basic synthetic products might not have, like antioxidant, anti-inflammatory, cardio-protective, anti-cancerous, immuno-modulatory and antimicrobial properties.^[9,10]

Until this point, there's been a need to explore new technologies and approaches aimed at optimizing the production yield of profitable products at a minimal cost. Lately, numerous researchers have directed their attention towards enhancing product yield while minimizing energy consumption. This shift will significantly affect the overall cost of product manufacturing. Encouraging complete utilization or integrated biorefinery of FW should be advocated, leading to a drastic reduction in its management expenses.^[8] Bioeconomy aims to grow promptly in the future and generate €2.2 trillion in Europe, with bio-based chemicals reaching a share of 15% of the global chemical market and over US \$103 billion by 2025.^[6]

Leveraging food by-products to reduce waste not only addresses environmental and economic concerns but also opens new avenues for their functional utilization. In this context, hydrogels emerge as a promising platform for valorizing these by-products, enabling their application in nutraceutical formulations through advanced encapsulation and delivery systems.

Hydrogels: structure, composition and function

Hydrogels are 3D polymeric materials able to absorb large amounts of water, swell and expand while maintaining structure. Their hydrophilic characteristics allow them to hold high quantities of water, while their cross-linked network allows to retain said water in their structure without dissolving the matrix.^[11,12] These materials have been widely used for contact lens production, tissue engineering, drug delivery systems, biosensors and agriculture.^[11]

Hydrogels have been extensively used for their physicochemical, mechanical and biocompatible characteristics which depend on polymer type, polymer ratio, degree of cross-linking, charge density, composition and production method, influencing their sensitivity to external stimuli.^[11–13] Examples of external stimuli encompass solvent composition variations, temperature fluctuations, the application of electric and magnetic fields, alterations in pressure, shifts in pH, and changes in light intensity, and the magnitude of the hydrogel's response is proportional to the level of external stimuli.^[11,12] Alterations to inert external stimuli can lead to the hydrogels reversing to their initial conformation.^[11]

The classification of hydrogels is based on several factors which include composition (as natural, synthetic or hybrid), structure (as crystalline, amorphous or semi-crystalline), cross-linking (as physical, chemical or dual network), surface charge (as ionic, neutral, amphoteric or zwitterionic), durability and response to external stimuli

The hydration/swelling of the network is a multi-step process (Fig. 1). Initially, water molecules hydrate the most polar, hydrophilic active sites within the hydrogel matrix, resulting in the formation of primary bound water. This water type becomes an integral component of the hydrogel's structure and is challenging to separate from it. As the process continues, hydrophobic sites become exposed, interacting with water molecules to create the hydrophobically bound water, also known as secondary bound water. Subsequently, due to the resistance offered by covalent or physical crosslinks against the osmotic driving force of the polymer network towards infinite dilution, an additional amount of water is absorbed. This amount corresponds to the equilibrium swelling capacity of the polymer. Meanwhile, the bulk or free water fills the spaces between the network chains, larger pores, micropores, or voids. The quantity of water absorbed by a polymer hydrogel relies on several factors including the temperature of the surrounding medium, the characteristics of the polymer (such as surface and textural properties), and the interactions occurring between water molecules and the polymer chains.^[12,14,15]

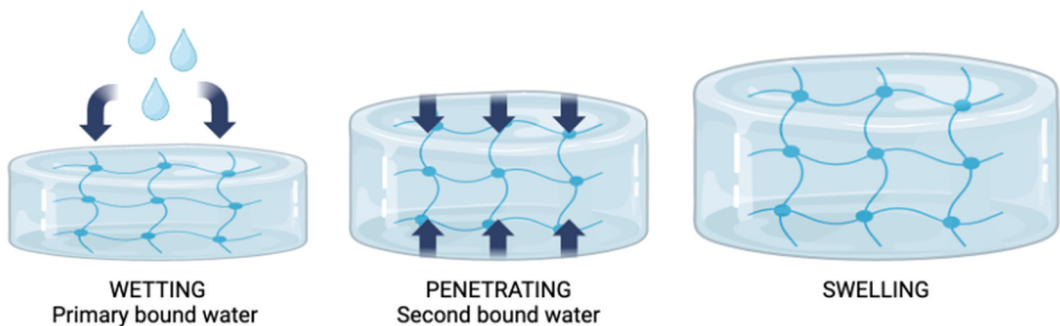


Figure 1. Hydrogel swelling multi-step process representation.

The production of hydrogels can occur through the dissolution of a single polymer, in solvent to create a 3D structure, or multiple polymer units, to cross-link and create complex 3D structures. The polymers are responsible for maintaining the overall integrity of the matrix and its ability for water intake by employing processes like capillary, osmotic and hydration forces, assured by the presence of hydrophilic polar groups (such as $-\text{NH}_2$, $-\text{COOH}$, $-\text{OH}$, $-\text{CONH}_2$, $-\text{CONH}$ and $-\text{SO}_3\text{H}$), counter-balancing the intermolecular forces between the polymer network and crosslinkers.^[12,16]

The mechanisms governing molecule release from hydrogels can vary considerably, contingent upon a range of factors linked to solute attributes, formulation composition, or polymer characteristics. Broadly, molecule release can be categorized into three types, determined by the step that limits the release rate: a) diffusion-controlled release relies on the molecule's diffusivity across the polymeric matrix; b) swelling-controlled release is contingent on the time taken for the solvent to penetrate the polymeric matrix and establish the gel layer; c) chemically-controlled release is based on reactions occurring within the polymeric matrix, such as hydrolytic or enzymatic degradation, often referred to as "erosion" of the matrix.^[15]

Two conventional formulations based on hydrogels are prevalent in oral molecule delivery: matrix systems and reservoir systems. Matrix systems disperse the molecule entirely within the polymeric bulk, often achieved through mechanical mixing of dry powders. One of the primary characteristics crucial for selecting a molecule in controlled release systems (CRS) is its solubility. Nonetheless, molecules with low solubility attributed to hydrophobicity often pose a challenge when integrating them into hydrogel matrices for controlled release mechanisms. Solubility plays a pivotal role since hydrophobic molecules, in particular, tend to aggregate in aqueous environments. Hence, within CRS, the consideration of molecule-hydrogel adsorption becomes imperative.^[17]

Hydrogels are employed in a wide range of industrial and biological applications, such as drug delivery, wound healing, bone regeneration, biosensing, antimicrobial products, cancer treatment and hygienic products, given their distinct structure, adaptability and water content.

There is a growing interest in utilizing hydrogels as a molecule delivery system because of their three-dimensional structural network, which possesses a high-water holding capacity.^[14]

Unlike previous reviews that broadly address hydrogel technologies or food-waste valorization, this work specifically integrates: (i) a bromelain-centered case study as a model proteolytic enzyme, with a deep search on the most recent experimental scientific articles and conference papers on the topic; (ii) a comparative matrix – enzyme compatibility analysis grounded in molecular interaction mechanisms; and (iii) a translation-oriented perspective covering scale-up, TEA/LCA and regulatory pathways. This approach is complemented by a circular economy perspective and a translation-oriented evaluation encompassing scale-up, cost, regulatory considerations, thereby offering a decision framework for identifying natural hydrogel platforms that preserve bromelain bioactivity and enable targeted delivery. This dual scientific-practical framing addresses a critical gap in the literature, where enzymatic compatibility and commercialization barriers for food-waste-derived hydrogels remain underexplored.

Literature results on natural and sustainable hydrogels

Hydrogels: synthetic vs natural matrices

Hydrogels have a track record of demonstrating a favorable safety profile due to the use of non-toxic, non-reactive polymers in their synthesis, making them suitable and safe for pharmaceutical applications.^[18] Different polymers can be used to produce hydrogels for achieving various applications. Manipulating the properties of these polymers allows for the modification and improvement of various hydrogels characteristics, such as pore size. This adjustment in pore size solidifies hydrogels as unique candidates for molecule delivery, NDDS (Novel Drug Delivery Systems), compared to other delivery systems, enabling the control of molecule diffusion rates within their network.^[18]

The composition of the hydrogel matrix can be divided in natural, synthetic or hybrid hydrogel depending on the type of polymers used and the ideal hydrogel should comprise characteristics like high absorbability, biocompatibility, viscoelasticity, stability, durability, permeability, flexibility, re-wetting capability, molecule loading capacity, low price and non-toxicity.^[14,19] Through precise design and experimental methodologies, optimal advantages can be achieved for treating, controlling or preventing diseases that necessitate targeted molecule delivery.

Synthetic hydrogels can be composed by synthetic polymers like polyvinyl alcohol (PVA), polyethylene glycol (PEG), polyacrylamide (PAA), and others, and are characterized for their high-water retention capacity, extended shelf-life and increased gel strength, being the dominant marketed matrix because of their facilitated production processes. Whilst, natural hydrogels (like cellulose, starch, chitosan, guar gum, galactomannans, etc.) provide additional advantages like enhanced biocompatibility, biodegradability (able to be absorbed or degraded by natural processes over time), cellular interactions (mimicking the extracellular matrix, supporting cell adhesion, proliferation and differentiation), low immunogenicity (less likelihood of triggering an immune response), environmentally friendly (utilizing natural sources), availability, cost, potential bioactivity, ease of modification, facility of usage, mechanical strength and porous structure being more desirable for biomedical purposes and the environment. In contrast to natural hydrogels, synthetic hydrogels carry many concerns regarding waste disposal and increased prices arising the desire to use renewable resources for producing sustainable and natural bio-based hydrogels, with increasing demand and interest for innovative biotechnology and biomedicine.^[12,20]

Food by-products applied to bio-based hydrogels

Over the last years, there has been an increased interest in exploring food by-products and residues for different applications, namely the production of food bio-based hydrogels with a multitude of uses. This review article comprises a search on available research literature examples for nutraceutical applications of food bio-based hydrogels (Table 1). The search was done using keywords like “hydrogel”, “food by-products” and “nutraceutical applications” resulting in around 2900 results on Google Scholar (Table 1(a)). A 10 year search for “hydrogel” and “food by-products” was done on Scopus, from 2015 to 2025, and 68 results were obtained from which only those regarding research articles for nutraceutical applications are presented on Table 1(b). For both platforms the scientific articles and conference papers using food by-products/losses are shown in Table 1, in order to assess the current state of experimental research done on the topic.

The compiled literature on Table 1 proves the current demand on studying and exploring food by-products and food waste for the production of new and innovative ingredients with special focus on nutraceutical applications (Fig. 2).

Food waste, once seen as a problem, is now being recognized as a valuable resource that can be repurposed for beneficial purposes. As we face increasing concerns about sustainability and the efficient use of resources, there is a growing interest in exploring food byproducts and losses for nutraceutical applications.

Nutraceuticals, which are products derived from food sources with purported health benefits, offer an avenue for utilizing food waste in a sustainable manner. By extracting bioactive compounds from food byproducts, such as antioxidants, vitamins, and dietary fibers, we can create nutraceutical products that promote health and well-being.

This approach not only helps to reduce the environmental impact of food waste but also contributes to the development of innovative and sustainable solutions for meeting nutritional needs. By harnessing the potential of food waste for nutraceutical applications, we can turn a challenge into an opportunity to improve both human health and environmental sustainability.

Table 1. Publications containing keywords like “hydrogels”, “food by-products” and “nutraceutical applications” on (a) Google Scholar and (b) Scopus database during 2015–2025.

Type of hydrogel	Food by-product or loss	Added-value product	Application	Reference
Google Scholar (a)				
pH-responsive double-network hydrocolloid-based hydrogel	Citrus limon peels	Lemon polyphenol extract	Practical application in the food and pharmaceutical industries	Bhattacharya et al., ^[21]
Orange peel hydrogel	Orange peel	Pectin-rich orange peel powder	Alternative source of high methoxy pectin and sugar substitute in the food industry	Li et al., ^[22]
Chitosan/alginate hydrogels incorporating NaDES extracts	Saffron floral by-products	Saffron floral by-products extracts	Promising candidates for food or cosmetic applications; rich in bioactive compounds such as polyphenols, carotenoids, terpenoids	Cerdá-Bernad et al., ^[23]
Lyophilized composite kaempferol hydrogel	Lotus stems	Resistant starch extract	Antioxidant, anti-diabetic, anti-hypertensive, anti-lipidemic and anti-microbial properties in simulated gastro-intestinal conditions	Noor et al., ^[24]
Lysine modified kutki millet starch hydrogel	Kutki millet grains	Kutki millet starch	Use as nutraceutical/drug delivery carriers	Mahajan & Bera, ^[25]
Casein and alginate hydrogels	Kinnow mandarin peels	Bioflavonoids extract	Functional foods rich in bioactive compounds	Kaushal & Singh, ^[26]
kappa-carrageenan hydrogels containing galactomannans	Spent coffee ground	Galactomannans extract	Enhanced bioactivity in milkshake (rich in phenolic components and bioactive polysaccharides)	Ray Aratrika, ^[27]
Okara cellulose hydrogel cross-linked with chitosan, carrageenan or arabic gum	Soybean waste (okara)	Okara cellulose	Production and characterization of mixed okara cellulose hydrogels for food applications	Wu et al., ^[28]
pH-shifting and high-intensity ultrasound treated pea protein imbedded in pea protein isolate gel matrix	Dry yellow peas	Pea protein	Functional ingredient as well as a structure builder in meat substitution products	Ma et al., ^[29]
Aloe vera mucilaginous based hydrogels	Aloe vera leaves	Aloe vera pulp extract	Anti-inflammatory activity, wound healing and promote skin regeneration, thus they can be utilized in healing products (psoriasis treatment)	Jales et al., ^[30]
Okara cellulose hydrogel	Soybean waste (okara)	Okara cellulose	Production and characterization of okara cellulose hydrogels for numerous applications	Changling Wu et al., ^[31]
Functional starch-based hydrogels supplemented with Paulownia leaves' extracts	Artichoke bracts	Artichoke bracts extracts	Delivery of bioactive compounds	Órbenes et al., ^[32]
Calcium alginate hydrogels filled with cumin essential oil	Cumin seeds	Cumin essential oil	Delivery of bioactive compounds in food systems	Gholamian et al., ^[33]
Modified starch hydrogels	Kutki millet grains	Kutki millet starch	Delivery of nutraceuticals	Mahajan et al., ^[34]
Proanthocyanidin-rich grape seeds phenolics encapsulated in hydrogel	Grape seeds from winemaking	Proanthocyanidins, monomeric flavanols, flavanols and anthocyanins extracts	Delivery in bioactive compounds for food products application	Pedrali et al., ^[35]
Scopus (b)				
3D food printing inks	Okara, sesame cake, brewer's spent grain and butterhead lettuce	Food waste flours	Potential of valorizing food waste by leveraging its fiber and protein content to create functional 3D food printing inks	Yong et al., ^[36]

(Continued)

Table 1. (Continued).

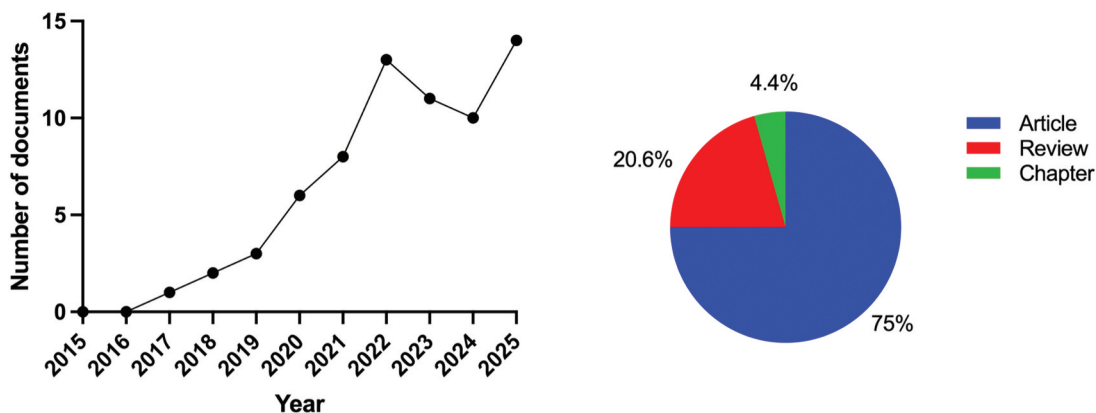
Type of hydrogel	Food by-product or loss	Added-value product	Application	Reference
Hydrogel Electrolytes	Agricultural byproducts	Food starch materials	Starch-based electrolytes as possible alternatives to commercial formulations for skin-interfaced measurement electrodes	Alarcón-Segovia et al., ^[37]
Injectable gelatin/modified starch waste hydrogels	Modified cassava starch waste and spent coffee grounds	Aldehyde starch and ferric ions	Various medical applications by enabling localized drug delivery with environment-triggered release	Jittham et al., ^[38]
Hemicellulose/PVA-based bioactive films	Avocado pruning waste	Avocado pruning waste derived hemicelluloses	Potential as bio-based polymer source for the packaging industry	Lucena et al., ^[39]
“Honey pearl” 3D hydrogels with berry by-products	Peels, seeds and pulp residue of blueberries and strawberries	Blueberry and strawberry by-products’ extracts	Use of hydrogels suitable for plant cell inclusion in bio-inks for 3D additive manufacturing for customized foods	Errico et al., ^[40]
Bigel from chicken protein hydrogel and carnauba wax-based oleogel	Fresh chicken drumsticks	Chicken protein isolate	Promising candidate for food applications, particularly as functional ingredients or carrier of bioactive compounds in various food products	Oyom et al., ^[41]
Alginate-pea protein ternary composite gels	Bamboo shoot by-products	Insoluble dietary fiber from bamboo	Encapsulate bioactive compounds for targeted intestinal release, protect acid-sensitive drugs, and serve as coatings for acidic foods	Chen et al., ^[42]
Bigel from κ-carrageenan hydrogel and beeswax oleogel	Hibiscus flower and coconut shreds	Hibiscus flower and coconut shreds co-extracts	Applied as low-fat spreads and hair gel formulations and the residue used for confection balls, increasing the fiber content of the balls	Malage et al., ^[43]
Fat-Replaced beef burgers with Hydrogel emulsions from olive oil	Artichoke stems, leaves, and external bracts of the crop	Artichoke extract	Beneficial effects on the antioxidant activity, total phenolic content of the reformulated burgers, decrease in color changes, lipid and protein oxidation and reduction of the formation of volatile compounds	Ayuso et al., ^[44]
Chitosan/PVA hydrogels	Wild-caught deep-sea fish	Marine collagen peptides	Increase wettability, antimicrobial capabilities, and hemostatic properties for safe and effective hydrogel wound dressing	Islam et al., ^[45]
Ca(II)-alginate beads	Cowpea pods	Cowpea (<i>Vigna unguiculata</i>) extract	Carriers of bioactive compounds (cowpea phenolic compounds and peptides)	Traffano-Schiffo et al., ^[46]
Garlic Carbon dots/pectin-based hydrogel	Garlic	Carbon from garlic hydrolysis	Wound dressing for the control of multidrug-resistant bacterial infections	Sheng et al., ^[47]
Chitosan-alginate hydrogel microcapsules	Pumpkin seed	Pumpkin seed protein hydrolysate	Increase shelf life and improve the taste and antioxidant properties of aloe vera drinks	Nooshi Manjili et al., ^[48]
Sage seed gum and globulin protein IPN hydrogels	Sage seeds	Sage seed gum	Food, pharmaceutical and biomedical applications	Hosseini & Zahabi, ^[49]
Onion peel extract hydrogel	Potato, onion and garlic peels	Onion peel extract	Incorporated as natural extract against wounds and osteoarthritis	Salem et al., ^[50]
Insoluble soybean fiber hydrogels	Soybean okara	Insoluble soybean fiber	Applications in reconstituted foods and low-calorie gel systems	Zhao et al., ^[51]

(Continued)

Table 1. (Continued).

Type of hydrogel	Food by-product or loss	Added-value product	Application	Reference
Heat-induced hydrogels and emulgels	Bovine blood	Red cell fraction	Heme iron-enriched food products with reduced fat content or improved lipid profile (baked goods and meat products)	Fernández et al., ^[52]
Marine collagen hydrogel	Greenland halibut skin	Marine collagen extract	Hydration effect, suggesting its potential for cosmetic and skin care applications	Martins et al., ^[53]
Bead hydrogel loaded with grape pomace extract	Lambrusco grape pomace	Lambrusco extract	Controlled release of a grape pomace polyphenols-rich extract and to detect pH variations	Viscusi et al., ^[54]
Collagen hydrogels	Atlantic salmon skins	Salmon gelatin	Applications such as food packaging, cosmetic patch, wound healing dressing, or tissue substitute	Buscaglia et al., ^[55]
Dermal hydrogel	Cider and apple juice pomace	Apple pomace extract and pectin extract	Bioactive compounds, especially polyphenols and pectin, with good potential to be incorporated in dermal formulations	Arraibi et al., ^[56]
Whey protein isolates modified hydrogels	Whey protein	Whey protein isolate	Regeneration of non-load bearing bone tissue defects	Dziadek et al., ^[57]
Okara cellulose hydrogel	Soybean waste (okara)	Okara cellulose	Production and characterization of okara cellulose hydrogels for numerous applications	Changling Wu et al., ^[31]
Nanostructured lipid carriers and Nanostructured lipid carrier-based hydrogels	Passion fruit seeds	Passion fruit seeds oil	Skin application, proving to be good candidates as depigmenting agent	Krambeck et al., ^[58]
Ca(II)-alginate hydrogels	Cowpea pods	Phenolics-rich extract	Source of bioactive compounds for food applications	Traffano-Schiffo et al., ^[59]
Adlay bran oil emulgel	Adlay bran	Adlay bran oil	Accumulation of bioactive component on the skin is a more suitable functional food formulation for topical uses	Chang et al., ^[60]
Ophthalmic hydrogel	Olive mill wastewater	Treated olive mill wastewater	Ophthalmic nutraceutical	Di Mauro et al., ^[61]
Extract loaded hydrogels	Vitis vinifera and Vitis labrusca leaves	Leaf extracts and pure compounds	Topical formulation for skin protection against ultraviolet radiation damage	Dresch et al., ^[62]

NaDES = Natural Deep Eutectic Solvents; PVA = Polyvinyl Alcohol; IPN = Interpenetrating Polymer Network.

**Figure 2.** Total published documents on Scopus for a search on “food”, “by-products” and “hydrogel” from 2015 to 2025.

Bromelain-hydrogels: research advances – use cases

Pineapple, *Ananas comosus* Merr., is a popular tropical fruit used for the production of beverages, fruit candy, jam, jelly, wine, vinegar, bromelain extraction, etc. and it represents a production of 28 million tons per year worldwide. Its composition comprehends polyphenols (such as ferulic acid, etc.), carotenoids (such as b-carotene, etc.), flavonoids (such as myricetin), terpenoids, tannins, vitamins, minerals (such as calcium, etc.), fibers (such as cellulose, etc.), proteins (such as bromelain). Pineapple waste has shown vast bioactive potential with great interest to the nutraceutical, food, cosmetic and pharmaceutical industries.^[63]

Bromelain is a proteolytic mixture of enzymes which include peptidases, glucosidases, peroxidases, cellulases, carbohydrates phosphatases and glycoproteins and can be found in all parts of the pineapple. It has shown antimicrobial, anti-inflammatory, cardioprotective, immunomodulatory, antithrombotic and antitumor properties.^[64] The effectiveness of numerous bioactive agents, encompassing drugs, vitamins, and nutraceuticals, is hindered by factors like poor chemical stability, low water-solubility, and limited oral bioavailability. To address these challenges, delivery carriers are developed including small particles such as microemulsions, nano emulsions, emulsions, solid lipid nanoparticles, and hydrogel particles to encapsulate and safeguard the bioactive agents, facilitating their delivery, bioavailability and pharmacokinetic profile under optimal conditions.^[19,65]

In this review article, a 10-year search on the available literature on Scopus for hydrogels containing bromelain for different applications was done using keywords like “hydrogels” and “bromelain” in the publication’s titles and abstracts, resulting in 46 results from 2015–2025. Table 2 presents the results obtained considering only articles and conference papers, in order to assess the current state of experimental research done on the topic.

Recent studies (Table 2) made on bromelain hydrogels show a growing interest for these loaded delivery systems in nutraceutical and pharmaceutical applications, as anti-tumor and antiplatelet agent, intestinal and topical delivery for controlled release systems and wound treatment. Zhang et al. (2023) developed a pH/thermal sensitive bromelain-loaded hydrogel as anti-tumor in situ injection and achieved a tumor growth inhibition rate of 93.9%.^[71] Prabowo et al. (2021), studied the encapsulation of bromelain in alginate-pectin beads as antiplatelet agent in oral administration and achieved in vitro antiplatelet activity of 56%, proving its capacity to prevent thrombin-induced platelet aggregation and adhesion to endothelial cells.^[86] Studies conducted by Irfan et al. (2020), showed that bromelain-loaded alginate-guar gum hydrogels exhibit an antiplatelet activity of around 35% for the dissolution sample, releasing higher concentrations of bromelain in the intestinal phase.^[85] Similar results were obtained in a study by Pratiwi et al. (2020) for bromelain-loaded chitosan-guar gum hydrogels, showing greater bromelain release and activity in the intestinal environment.^[84] Mala et al. (2021), conducted a study on pectin and starch-based hydrogel beads loaded with bromelain and concluded that encapsulation of bromelain potentiated its activity in all tested temperatures and obtained faster release rate at intestinal simulated environment, proving the high interest on these systems for bromelain intestinal delivery in food and pharmaceutical applications.^[70] As for its potential for wound treatment, Coco et al. (2021), developed bromelain-loaded acrylamide-PVA and PEG hydrogels and results showed that PVA systems potentiated the absorption and release of bromelain for anti-inflammatory biological topical applications.^[78] Wang et al (2021), developed a “three-in-one” bromelain-loaded hydrogel for wound cleaning, antibacterial and healing abilities by encapsulating bromelain in a poly(l-lactide) (PLC) hydrogel.^[76] Bayat et al. (2021) developed a chitosan hydrogel loaded with bromelain alginate-chitosan nanoparticles for effectively reducing necrotic tissues and re-epithelization as debridement agent.^[77] This review uniquely provides a comparative, molecular-level evaluation of bromelain encapsulation within different food-waste-derived hydrogel matrices with respect to: (i) gelation mechanism and cross-linking tolerance to proteases; (ii) microstructure/porosity vs. diffusion; (iii) pH/ionic responsiveness relevant to gastrointestinal or wound settings; and (iv) activity retention and release profiles for bromelain. Alginate systems, stabilized via Ca^{2+} ionic crosslinking, create anion-rich

Table 2. Publications containing keywords like “hydrogels” and “bromelain” on Scopus database during 2015–2025.

End-use	Type of hydrogel	Type of publication	Application	Reference	
Internal controlled drug delivery	Chitosan-poly(N-vinylpyrrolidone) semi-IPN hydrogel	Conference paper	Drug delivery in specific targets such as colon and gastrointestinal	Fitria et al., 2018 ^[66]	
	Chitosan-poly(N-vinylpyrrolidone) full-IPN hydrogel	Conference paper	Drug delivery in specific targets such as colon and gastrointestinal	Sandhy et al., 2018 ^[67]	
	Glutaraldehyde-crosslinked chitosan hydrogel	Article	Drug delivery in specific targets such as colon and gastrointestinal	Setiasih et al., 2018 ^[68]	
	Chitosan-methyl cellulose semi-IPN hydrogel	Conference paper	Drug delivery in specific targets such as colon and gastrointestinal	Putranto et al., 2018 ^[69]	
	Pectin-Resistant Starch Based Hydrogel Beads	Article	Bromelain delivery applications in food and pharmaceutical products development for controlled intestinal release	Mala & Anal, 2021 ^[70]	
	pH/thermal sensitive nanohydrogel	Article	In situ tumor injection as local drug delivery systems	C. Zhang et al., 2023 ^[71]	
	Bromelain-encapsulated alginate beads reinforced with gum arabic	Article	Drug delivery in gastrointestinal tract	Peaparkdee et al., 2025 ^[72]	
	Poly(N-Isopropylacrylamide)-co-Acrylamide hydrogels	Article	Controlled release (for example topical use)	F. Croisfelt et al., 2015 ^[73]	
	Alginate and Arabic Gum hydrogels	Article	Development of wound dressings that support the debridement of burns and wounds	Ataide et al., 2017 ^[74]	
	Poly(N-isopropylacrylamide) hydrogels	Article	Controlled release (for example topical use)	Croisfelt et al., 2018 ^[75]	
	Polymeric PLC hydrogel	Article	Wound dressing development and clinical application	Wang et al., 2021 ^[76]	
	Bromelain-loaded sodium alginate nanoparticles incorporated into chitosan hydrogel	Article	As a convenient debridement system for treatment of burns	Bayat et al., 2021 ^[77]	
	PVA and PEG hydrogels	Article	Topical uses in burn injuries	Coco et al., 2021 ^[78]	
	Bromelain-loaded alginate and chitosan hydrogel	Article	Accelerate burn wound healing	Thomas et al., 2025 ^[79]	
	Antiplaetlet agent	CMC/polyethylene glycol films with bromelain and curcumin	Article	Improve and accelerate skin regeneration for chronic wound healing	Mojahedi et al., 2024 ^[80]
Chitosan and alginate hydrogels 3D-printed patch with bromelain and aloe vera		Article	Burn wound care with improved bioactive delivery and enhanced healing	Patitucci et al., 2025 ^[81]	
Dual-layer scaffold/hydrogel with bromelain silver nanoparticles		Article	Clinical applications in skin tissue engineering	Najafian-Najafabadi et al., 2025 ^[82]	
Niosomal Hydrogel Loaded With Bromelain		Article	Bromelain niosomal hydrogel for managing skin fibrosis in scleroderma	Ardeshiri et al., 2025 ^[83]	
Chitosan-guar gum hydrogel		Conference paper	Administration of bromelain as an antiplatelet agent	Pratiwi et al., 2020 ^[84]	
Alginate-guar gum hydrogel		Conference paper	Administration of bromelain as an antiplatelet agent	Irfan et al., 2020 ^[85]	
Bromelain-loaded pectin and AP19 beads		Article	Oral administration of bromelain as an antiplatelet agent	Prabowo et al., 2021 ^[86]	
Enzymatic agent		Silicone elastomers	Article	Bromelain devulcanization of elastomers	Donahue-Boyle et al., 2025 ^[87]
		Silicone-gelatin hydrogels elastomers	Article	Bromelain degradation elastomers	Silverthorne et al., 2024 ^[88]

IPN = Interpenetrating Polymer Network; PLC = Poly(L-lactide); PVA = Polyvinyl Alcohol; PEG = Polyethylene Glycol; CMC = Carboxymethyl Cellulose.

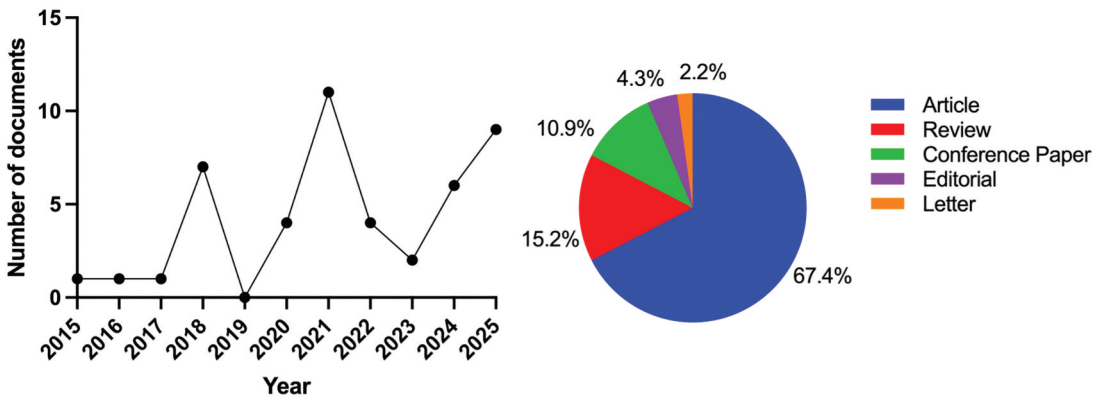


Figure 3. Total of published documents on Scopus for a search on "hydrogels" and "bromelain" from 2015 to 2025.

microenvironments that minimize proteolysis of the matrix itself. In parallel, pectin hydrogels, particularly low-methoxyl pectins, provide divalent-ion crosslinking and high water-holding capacity, maintaining bromelain's tertiary structure. Chitosan's cationic nature enhances mucoadhesion but may induce partial denaturation at low pH unless blended with anionic polysaccharides. Cellulose derivatives provide mechanical robustness but may require co-polymers to improve release kinetics. Galactomannans exhibit hydrogen-bond-dominated gelation, offering mild encapsulation conditions favorable to protease stability. This cross-matrix analysis clarifies trade-offs (e.g., calcium-alginate's ionic fragility versus facile gastrointestinal targeting; chitosan's mucoadhesion versus pH sensitivity) and guides fit-for-purpose selection in nutraceutical or topical formats.^[89,90]

These studies show the increasing interest on the encapsulation of bromelain in hydrogels for diverse applications, represented by the increased tendency of published documents on bromelain hydrogels over last decade (Fig. 3), although further and deeper studies should be done on this topic, promoting a green extraction and refinery of pineapple waste for encapsulation of natural extracted bromelain for in situ delivery.

The encapsulation of bioactive substances in hydrogels provides a means to shield them from external environmental factors throughout various stages, including production, storage, and consumption. These factors encompass oxygen, heat, light, pH variations, enzymes and more. The growing utilization of hydrogels as encapsulation and delivery agents is attributed to their elevated encapsulation efficiency, biocompatibility, cost-effectiveness, and environmentally friendly characteristics.

Hydrogels production through a circular economy approach

Globalization, population expansion, and the resulting imperative to generate large quantities of food, along with the prioritization of individual economic benefits over environmental health, have contributed to the emergence, in certain instances, of a linear-producing model in modern agriculture. Unlike traditional and local agriculture, which relied on circular sustainability models, contemporary agriculture generates substantial amounts of waste that often end up in landfills, leading to contentious outcomes rather than being reintegrated into the production cycle with a new purpose. Nevertheless, these agricultural residues are abundant in bioactive compounds, including phenolic compounds that exhibit various beneficial properties such as antioxidant, anti-inflammatory, cardioprotective, and anticancer capacities. The repurposing of these compounds not only holds promise for numerous potential applications, including as additives in food and feed, functional foods, nutraceuticals, cosmeceuticals, etc., but also stands as an environmentally favorable initiative by creating value-

added products. The circular economy concept seeks to mimic nature by prioritizing the 6Rs: reduce, reuse, recycle, redesign, remanufacture, and recover.

This approach arises in response to the challenges of limited resources, increasing pollution, and the planet's struggle with waste accumulation. The objective is to minimize raw material input, while encouraging the reuse, recycling, or recovery of food residues. The application of a circular economy approach extends across various fields, emphasizing mindful resource utilization and incorporating technological advancements for sustainable and profitable product development.^[9,91]

Over the last years, there has been a high demand for innovative ways of functionalizing food end-products with far interesting nutritional and physico-chemical profiles. The significant potential of these natural biopolymers lies in their ability to address contemporary consumer health and environmental sustainability concerns. They stand out for being renewable, cost-effective, biocompatible, biodegradable, and edible. Additionally, they offer a diverse array of functionalities and gelation routes.^[13,92]

Hydrogels' ability for entrapping high amounts of moisture, specific structure and mechanism of processing and action are of high interest for oral and topical controlled release drug delivery. Ultimately, the flexibility of purposely designing and producing these systems with required mechanical characteristics and functionalities has great potential for multiple end-applications employing green chemistry and processes which can utilize food sources and waste for promoting circular economy and sustainable approaches.^[20] The food industry is progressively emphasizing the need to supply sufficient nutritious food for all while safeguarding natural resources. Consequently, the rising trend of plant-based foods and hybrid food products, emerges as a promising solution to address this sustainability challenge.

Given that research on the subject of food hydrogels is comparatively limited compared to biomedical or pharmaceutical hydrogels, there are extensive opportunities to contribute to the advancement of the food industry through the integration of knowledge from these more advanced areas. When creating new food products, hydrogels can serve as fundamental structures (matrices) and play a vital role in ensuring structural stability, sensory characteristics, and nutritional aspects, in addition to acting as carriers for a diverse array of nutrients and nutraceuticals. In the process of creating healthier food alternatives with plant-based components, the objective is to attain the desired visual appeal, texture, flavor, mouthfeel, and functionality, by incorporating healthful and sustainable plant-derived ingredients, including proteins, polysaccharides, lipids and carbohydrates.

Current limitations and future perspectives

Although laboratory studies demonstrate the technical feasibility of producing functional hydrogels from food by-products and of encapsulating enzymes such as bromelain, translating these advances into industrial practice faces concrete technical, economic, regulatory and supply-chain barriers. The main limitations provide representative quantitative evidence, where available, and propose pragmatic research priorities and decision points to accelerate scale-up and safe deployment.

Limited studies quantify Techno-Economic Analysis (TEA) and/or Life Cycle Assessment (LCA) for natural hydrogels and emerging work on biopolymer hydrogels shows how crosslinker choice, drying and sterilization dominate costs and increase carbon footprints. Integrating TEA/LCA early in the industrialization process will certainly guide to design sustainable decisions.^[93–96]

Translating these benchtop advances into robust, regulated products requires addressing several practical constraints (Fig. 4), most notably scale-up economics, enzyme – matrix compatibility and stability, raw-material variability and regulatory readiness.

Scale-up and cost-of-goods: most hydrogel formats in the market involve water removal (spray-drying, freeze-drying or hybrid routes). Conventional spray-drying and freeze-drying show distinct trade-offs: spray-drying achieves high throughput but can degrade heat-sensitive proteins and has substantial thermal energy demands; advanced steam-assisted spray dryers reduce energy use but add capital expenditure complexity (reviewed values and comparisons).^[97] Freeze-drying preserves

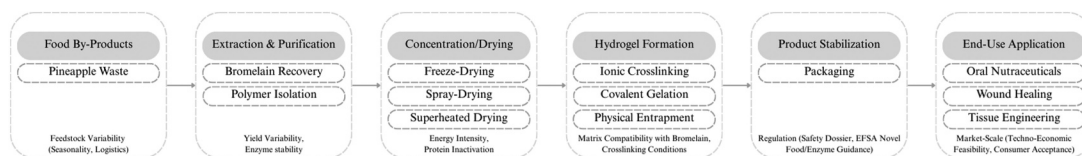


Figure 4. Decision-matrix schematic illustrating the pipeline from food by-products to bromelain-loaded hydrogels. Critical hotspots are highlighted at each stage, including feedstock variability, energy-intensive drying, matrix – enzyme compatibility and regulatory compliance.

activity but is highly energy-intensive and expensive at scale. Such drying and dehydration stages are frequently identified as LCA/TEA hotspots in hydrogel and aerogel production.^[97] Techno-economic comparisons consistently rank spray drying as more energy- and cost-efficient for large throughputs, while freeze drying better preserves heat-labile cargos.^[98–100] For bromelain, encapsulation by spray-drying or coacervation can retain ~70–85% activity immediately post-processing (matrix-dependent), whereas harsher inlet temperatures or high shear may reduce activity further; freeze-dried preparations typically show higher retained activity but at higher unit cost. Representative studies report ~76% activity retention after microencapsulation/drying, with improved retention when mild, protective wall materials are used.^[101] Decision frameworks should therefore couple unit operation modeling to enzyme activity budgets and target price points.^[98,100] TEA studies for biomass-derived hydrogels (e.g., lignin-based systems) report minimum selling prices in the low thousands of US\$/ton, illustrating that production costs can rival or exceed commodity prices unless process integration and valorization cascades are applied. These studies emphasize that capital expenditures, solvent recycling and drying are principal cost drivers.^[102]

Enzyme-matrix compatibility and functional stability: bromelain is susceptible to thermal inactivation and pH extremes; preserving catalytic activity through extraction, drying and formulation requires mild downstream conditions or protective encapsulation strategies (e.g. gentle crosslinking chemistries, cryo-/lyo-protectants). Empirical data show improved activity retention when enzymes are immobilized/entrapped but the degree depends strongly on matrix chemistry and processing parameters.^[103–106] Electrostatic and hydrogen-bonding interactions between bromelain and anionic (alginate, pectin) or cationic (chitosan) networks can either stabilize the enzyme or restrict substrate access.^[107] Ionic polysaccharides (alginate, pectin) interact electrostatically with protein charges; chitosan provides mucoadhesion and possible stabilization via hydrogen bonding and ionic interactions; protein-based matrices may offer inherently compatible environments but can complicate crosslinking control. These molecular interactions govern release kinetics, activity retention and shelf life and thus require systematic comparative studies.^[108,109] Because bromelain is proteolytic, protein-rich carriers (e.g. gelatin) risk self-degradation unless inhibitors, shielding domains or cross-link chemistries that resist proteolysis are used. Comparative immobilization reviews highlight strategies (e.g., covalent immobilization, nanoparticle supports) that preserved ~80% activity after multiple reuse cycles, principles translatable to edible matrices via safer chemistries.^[110]

Raw-material variability from food side-streams: food-waste-derived polysaccharides exhibit batch-to-batch variability that alters gelation and release. Such variability complicates specifications and reproducibility without tighter sourcing or in-line characterization.^[111,112] Standardization (e.g. degree of esterification, mannose/galactose ratio, molecular-weight distribution) and process analytics are prerequisites for consistent bromelain loading, release kinetics and shelf life.

Regulatory readiness and product classification: in the European Union (EU), food enzymes require authorization under Regulation (EC) No 1332/2008, following European Food Safety Authority (EFSA) safety evaluation; parallel compliance applies to hydrogel materials intended for food contact under Regulation (EU) No 10/2011 (for plastics) or relevant national/union measures for other materials.^[113,114] For bromelain sourced from by-products, applicants must provide identity, production process, compositional data, toxicology and exposure estimates; this substantially increases the

time and data cost to market compared with simple ingredient repurposing. If marketed as a dietary supplement with new conditions of use or forms not previously in the food supply, bromelain formulations may trigger a New Dietary Ingredient (NDI) notification. Regulatory authorities and end users require standardized activity units, impurity profiles, and evidence for absence of contaminants (microbial, allergenic or pesticide residues) to approve food or topical uses.^[115–118] Hydrogels positioned for wound care or drug delivery invoke device/medicinal-product routes with substantially higher evidence thresholds (quality, safety, performance). No shortcut exists from “food-grade” to “medical-grade”, so early regulatory landscaping is essential to avoid costly reformulation.^[114]

Lab-scale conditions often fail to reproduce at industrial scale due to heat/mass-transfer, humidity and mixing sensitivities, driving batch-to-batch variability and higher cost of goods sold, and so standardized process windows and good manufacturing practice compatible polymerization/sterilization are needed. Recent analyses for biopolymer hydrogels underscore scale-up hurdles and shelf-stability constraints.^[119–121] Developing compatibility maps that match bromelain’s stability profile to specific hydrogel chemistries will improve formulation success rates.^[122]

Future work on the topic should include: (i) process – potency co-optimization, by adopting design-of-experiments linking drying variables (e.g. inlet/outlet temperatures, shelf temperatures) to residual activity and microstructure, targeting $\geq 80\%$ post-process activity while meeting cost ceilings; pair with stabilizers such as polyols or sugars showed to protect proteins during dehydration;^[99,100] (ii) matrix engineering for protease compatibility, by selecting mildly acidic-to-neutral, calcium-crosslinked anionic networks (optimized porosity) or composite systems (e.g. pectin – starch) demonstrated to balance protection with release; avoid proteinaceous networks prone to proteolysis unless protected by resistant crosslinks;^[107] (iii) side-stream standardization, by implementing Quality Control (QC) specifications for degree of esterification (pectin) and mannose/galactose ratio (alginate) with supplier qualification, blending lots to target narrow specification windows and reduce performance drift;^[111,112] (iv) stability by design, by prioritizing storage conditions demonstrated to preserve bromelain activity ($\leq 4^\circ\text{C}$; desiccant packaging), and confirm real-time stability under intended logistics;^[104] and (v) regulatory pathways, by defining the product category early (food ingredient, processing aid, dietary supplement, medical device) and align with the corresponding US/EU requirements (GRAS or food-enzyme authorization; NDI when applicable; device/medicinal approvals for therapeutic claims).^[90,113,115,123]

Discussion

This review emphasizes the importance of introducing and exploring hydrogels as carriers for bioactive natural compounds and other functional components found in natural sources. By employing a circular economy approach, food waste can be further transformed and explored for multiple end-applications, namely for the food, nutraceutical, cosmetic and pharmaceutical industries by maximizing the circularity of a product life cycle and providing it a new innovative and sustainable end-result in today’s consumers routine.

Here, bromelain is used as an example of an added-value compound found in pineapple waste which has been shown to have potential activities for medicinal purposes. Literature research on bromelain-loaded hydrogels has proven that a great potential and interest arise from exploring in-depth the ability to refine and transform pineapple waste in new functional ingredients. Transforming and exploring any type of food waste into new functional ingredients and encapsulating it in a hydrogel matrix can offer several notable advantages: i) sustainability: utilizing food waste for hydrogel encapsulation contributes to sustainability by repurposing materials that would otherwise be discarded, reducing the environmental impact of waste disposal; ii) resource efficiency: repurposing food waste as functional ingredients minimizes the need for additional raw materials, promoting efficient resource utilization and reducing the demand for new agricultural or processing inputs; iii) cost-effectiveness: food waste, often considered a by-product, can be obtained at lower costs or even for free, making it a cost-effective source for developing functional ingredients for hydrogel

encapsulation; iv) circular economy: by incorporating food waste into hydrogel formulations, it aligns with the principles of a circular economy, emphasizing the reuse and repurposing of materials to create a closed-loop system; v) bioactive compounds: food waste is often rich in bioactive compounds, such as antioxidants and other nutritional elements, which can enhance the functional properties of hydrogels and potentially offer health benefits in applications like drug delivery or food packaging; vi) waste reduction: converting food waste into valuable functional ingredients reduces the volume of waste sent to landfills, addressing waste management challenges and contributing to a more sustainable waste disposal system; vii) diversification of hydrogel properties: different types of food waste can introduce a variety of properties, flavors, and functionalities to hydrogels, allowing for the customization of hydrogel applications based on the specific characteristics of the chosen food waste; viii) innovation in product development: exploring food waste for hydrogel encapsulation encourages innovation in product development, fostering the creation of novel, sustainable, and functional materials with diverse applications; ix) market trends and consumer demand: there is a growing market trend towards sustainable and eco-friendly products, and developing hydrogels from food waste aligns with consumer preferences for environmentally conscious and sustainable solutions.

Hence, by introducing the purified extracted compounds from upcycling food waste matrices in a hydrogel formulation, a natural hydrogel can be produced, and an array of functions can be expected from these systems. Throughout recent studies natural hydrogels have been considered advantageous regarding cost, biocompatibility, composition (integrating “generally recognized as safe” components) and encapsulation capacity (to a wide range of functional compounds). These hydrogels are usually evaluated for bioavailability and digestibility (gastrointestinal assay), toxicity profile, water-uptake and retention capacity (vital for swelling and permeability properties as controlled release systems), encapsulation efficiency and antioxidant properties (offering protection against oxidative stress) which are fundamental parameters for the assessment of the potential for these matrices to be used as drug carriers or food additives for improving food-products functional profile.

Further studies should be conducted on the natural hydrogels loaded with natural enzymes, namely bromelain, given its great potential, health-forward characteristics and feasibility in a society increasingly more open and susceptible to new innovative and sustainable food products, promoting the valorization of food waste by-products generated during the chain of production, through a zero-waste circular economy approach from farm-to-fork.

Despite promising advances, several translational barriers remain. Scaling up hydrogel production often results in inconsistent mechanical properties, elevated production costs and high energy consumption during drying processes. Regulatory hurdles further challenge progress, as enzymes like bromelain must meet stringent safety and quality standards for both nutraceutical and pharmaceutical applications. Addressing these limitations requires integrated approaches that combine material science with techno-economic assessment, regulatory alignment, and process innovations to ensure feasibility beyond laboratory settings.

Conclusion

In this context, we emphasize the significance of valorizing food waste by-products through the implementation of environmentally friendly, sustainable, and zero-waste strategies within the framework of the circular economy. Bromelain, an enzyme of notable industrial value and interest, emerges as an extractable component from upcycling pineapple waste by-products, offering a strategic means to optimize the utilization of generated waste throughout its production and consumption chain. Given its properties and characteristics, bromelain has been an emergent subject of study for applications in the nutraceutical and pharmaceutical industries, such as means of treatment for osteoarthritis, chronic inflammatory, malignant and autoimmune diseases and as a fibrinolytic, antiadhesive and anticancer agent.^[118,124] Notably, there is a growing interest in encapsulating bromelain for in situ delivery, with hydrogels serving as carriers that provide protection and ensure optimal conditions and targeted delivery.

Using bromelain as case study, we show how food-waste-derived hydrogel matrices can be rationally selected and engineered to preserve enzyme activity and deliver site-specific release, while advancing circular-economy goals. Looking forward, coordinated progress on scalable processing, TEA/LCA, regulatory alignment and stream standardization are essential to translate these systems from promising prototypes to deployable products in nutraceutical and health-adjacent markets.

This review critically consolidates current research on natural hydrogels incorporating bromelain for nutraceutical and pharmaceutical applications, offering a comprehensive synthesis of recent advancements in the field. The scarcity of scientific studies on this topic highlights the pressing need for further investigation into these natural delivery systems, emphasizing their potential for enhanced therapeutic efficacy while aligning with sustainable development goals.

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ORCID

Maria Manuela Pintado  <http://orcid.org/0000-0002-0760-3184>

Author contributions

A.M.V.-B.: Writing – original draft, formal analysis, conceptualization, data curation, methodology, investigation, software, review and editing, validation. D.A.C.: Formal analysis, review and editing, supervision, validation. M.P.: Supervision, methodology, review and editing, conceptualization, project administration. All authors have read and agreed to the published version of the manuscript.

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