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Incorporation of Plant-Based Functional Ingredients for Enhancing Antioxidant Potential in Food Systems-A Review

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Abstract:

Oxidative degradation in foods leads to losses in quality, shelf life and nutritional content, while oxidative stress in people has been associated with chronic diseases like cardiovascular diseases, neurodegeneration and cancer. Growing consumer demand for "clean-label" products and concerns about synthetic antioxidants are driving increased interest in plant-based functional compounds rich in phenolics, carotenoids, vitamins, and bioactive peptides. This study summarizes the current research on the introduction of plant-derived functional elements to improve the antioxidant capacity of food systems. Major classes and sources of plant antioxidants (phenolic compounds from fruits, vegetables, herbs, spices and by-products; carotenoid-rich extracts; standardized medicinal plant extracts; protein or polysaccharide-based ingredients) and their mechanisms of action (radical scavenging, metal chelation, physical barrier effects, etc.) are described. The review also covers technological approaches for stabilization and delivery of these ingredients, such as microencapsulation, nanoencapsulation, cyclodextrin inclusion, and biopolymer-based edible films and coatings, and illustrates their application in dairy, bakery, beverage, meat and packaging systems. It projects the main elements impacting the efficiency of antioxidants, such as matrix interactions, processing conditions, bioavailability and sensory impacts, and the prospects for sustainability through the valorization of plant by-products in the context of a circular economy. Finally, research gaps are addressed on the standardized evaluation techniques, structure–function linkages and translation of in vitro antioxidant capacity into in vivo health outcomes to direct future effort in building next-generation functional foods.

Keywords: microencapsulation, nanoencapsulation, cyclodextrin, functional foods**.**

Introduction

Oxidative reactions in foods, especially lipid and pigment oxidation, lead to rancidity, off-flavor development, discoloration, and nutrient loss, thereby limiting shelf life and consumer acceptance. In contrast, excessive production of reactive oxygen species in humans and lack of antioxidant defenses also contributes to oxidative stress, and therefore to cardiovascular disease, cancer, osteoporosis, and

neurodegenerative issues. The development of synthetic antioxidants butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT) solved these two problems. The development of plant-based alternatives has been motivated by toxicological concerns and unfavorable customer image. Foods are rich in bioactive substances, phenolic acids, flavonoids, tannins, anthocyanins, carotenoids and vitamins and have proved to have significant antioxidant, anti-inflammatory, antibacterial and other health advantages [1] Fig 1, 2 Table 1.

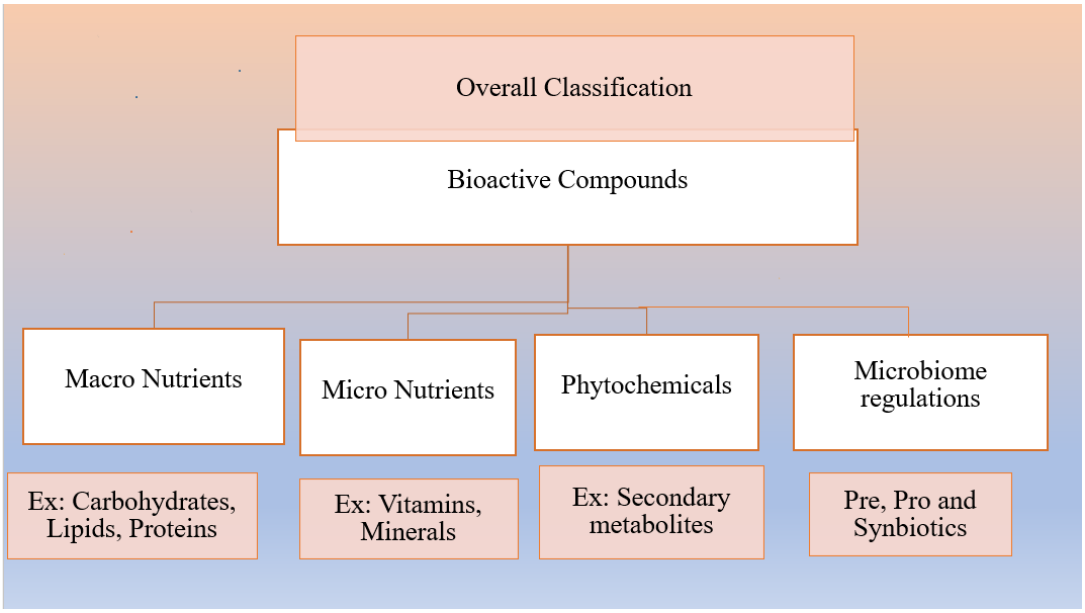

Figure 1 Overall Classification of Bioactive components

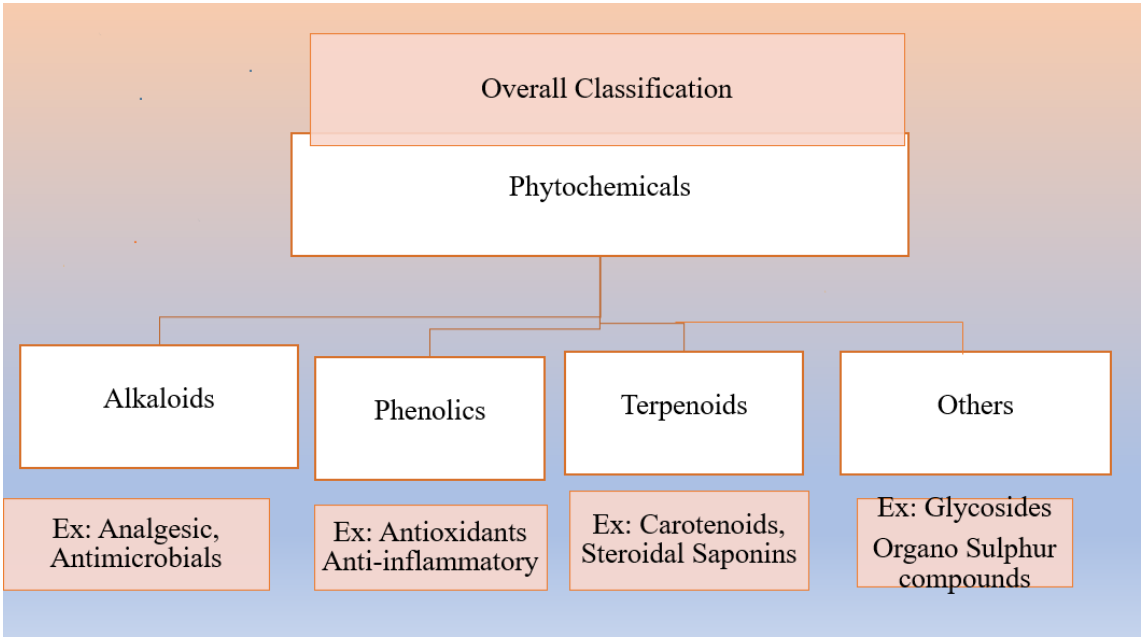

Figure 2 Overall Classification of Phytochemical Components

Research has found that higher consumption of fruits, vegetables, tea, or coffee and other plant-based products for many years have been associated with lower risk of oxidative stress-related diseases and the

concept of functional food with concentrated plant-based antioxidants was developed [2]. However, direct fortification of foods with these compounds might encounter challenges in terms of stability, solubility, food matrices, sensory properties, bioavailability, and hence food safety.

This review critically summarizes the current information on the utilization of plant-based functional substances for antioxidant potential in food processing for the same aim. This review presents i) plant-based antioxidant ingredients and their sources; (ii) their mechanisms of action in food matrices; (iii) analysis technologies for stabilization and delivery; (iv) applications in different food categories and in active packaging; and (v) current knowledge and future trends, and also focuses on sustainability and circular economy [3].

1. Classes and Sources of Plant-Based Antioxidant Ingredients

1.1 Phenolic compounds and polyphenol-rich extracts

Early systematic work on a broad range of plant extracts demonstrated that total phenolic content (TPC), measured using the Folin–Ciocalteu method, correlates positively with antioxidant capacity across assays such as 2,2-Diphenyl-1-picrylhydrazyl Assay (DPPH), ABTS (2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) Assay, Ferric Reducing Antioxidant Power Assay, Oxygen Radical Absorbance Capacity Assay (ORAC), and SOD (Superoxide Dismutase) [4]. For example, analyses of 30 industrially relevant plant extracts found that aqueous extracts of oak (*Quercus robur*), pine (*Pinus maritima*), and Cinnamon (*Cinnamomum zeylanicum*) exhibited among the highest antioxidant capacities and TPC values (300–400 mg gallic acid equivalents per gram) [5]. At the same time, mate (*Ilex paraguariensis*) and clove (*Eugenia caryophyllus*) also exhibited strong antioxidant activity, with TPC values around 200 mg GAE/g [6]. Similar studies on 92 edible and non-edible plant materials reported remarkably high antioxidant activity and phenolic content in berries (e.g., aronia, crowberry), willow bark, spruce needles, pine bark, and various medicinal plants, as well as in agro-industrial by-products such as potato and beetroot peels [7,8,9]. Reviews of dietary phenolic compounds emphasize their dual role in human nutrition—as antioxidants that can exceed the potency of vitamins C and E, as well as carotenoids, in vitro, and as modulators of cellular signaling and gene expression involved in endogenous antioxidant defences. These findings have motivated the use of crude phenolic-rich extracts from spices, herbs, and plant wastes as natural antioxidants in meat products, oils, bakery items, and beverages to replace complement synthetic antioxidants [10,11,12,13]

1.2 Carotenoids and pigment-based antioxidants

The red, orange, and yellow pigments in many fruits and veggies come from lipophilic pigments called carotenoids. These contain substances such as beta-carotene, lycopene, lutein and zeaxanthin. They comprise substances such as β-carotene, lycopene, lutein and zeaxanthin Fig 3,4. They function as antioxidants mainly by quenching singlet oxygen and scavenging peroxyl radicals, thereby protecting lipid phases in both dietary and biological membranes. However, carotenoids are particularly sensitive to oxidation, isomerisation and loss under light, heat and oxygen, and stability is a key challenge for functional food applications [15,16].

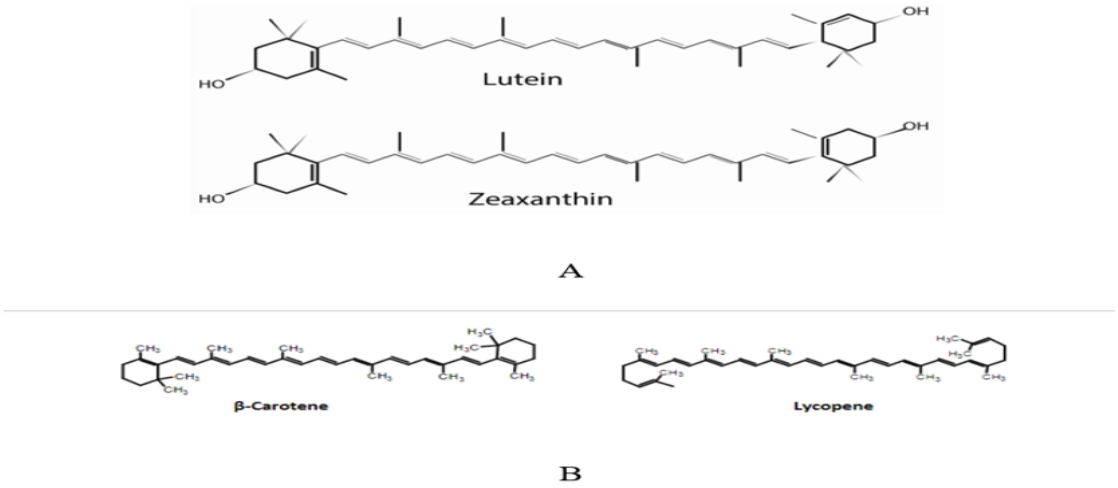

Figure 3 Chemical structures of lutein, zeaxanthin, β-carotene, and lycopene (adapted from Johra et al., 2020).

Recent scientific findings have focused on encapsulating β-carotene in internal-phase emulsion gels, nanoemulsions, and nano-lipid carriers to improve its stability and bioaccessibility. For example, β-carotene–encapsulated high-internal-phase emulsion gels generated via modified cold gelation exhibited better β-carotene preservation and higher antioxidant capacity than unstructured systems, owing to the dense gel network and limited oxygen diffusion [15]. Likewise, lycopene-loaded nano-lipid carriers based on ultrasonication showed improved oral bioavailability and regulated release, which apply to beverages and dairy-based functional meals [16].

1.3 Vitamins, protein hydrolysates, and other Bioactives

In addition to phenolics and carotenoids, plant-based compounds contain vitamins (e.g. ascorbic acid, tocopherols), bioactive peptides and antioxidant polysaccharides. Vitamins C and E are typical low molecular weight antioxidants. However, recent studies have highlighted the function of protein hydrolysates and peptides from plant and algal proteins that show radical scavenging, metal chelating and angiotensin-coupled with plant antioxidants in composite systems [17]. Encapsulation of Spirulina platensis protein hydrolysates in chitosan-coated liposomes resulted in microcapsules that retained approximately 90% of their initial antioxidant activity after 30 days at 4 °C and can be used to fortify foods. Fish protein hydrolysates with high antioxidant and ACE-inhibitory capacities, encapsulated in maltodextrin via spray drying, were incorporated into yogurt; the fortified products exhibited acceptable flavour and enhanced antioxidant and antihypertensive activities during a 7-day storage period. These examples show that peptide-based functional compounds, while not exactly plant sourced, can be coupled with plant antioxidants in composite systems [18].

Cellulose, pectin, alginate and chitosan are examples of polysaccharide-based carriers. These polysaccharides are not only used as encapsulation matrix but also play a role in antioxidant and barrier activities when mixed with plant extracts or essential oils in films and coatings. Cellulose dispersions and membranes containing pomegranate seed extract and essential oils showed modest inherent antioxidant activity, but exhibited strong antioxidant capacity after inclusion of these plant ingredients, with modifications in their swelling behavior, tensile strength and elongation at break [19].

1.4 Edible flowers, herbs, and medicinal plants

In addition to ordinary fruits and vegetables, edible flowers, herbs and medicinal plants are an expanding repertoire of plant-based functional substances. Editorials summarising recent research on edible plants highlight that many species are rich in phenolic compounds and other bioactives with antioxidant, anticancer, anti-inflammatory, and antimicrobial effects. For example, the antioxidant and anti-inflammatory effects of

cordyline flowers and other ornamental plants have been studied showing a substantial relationship between
coupled with plant antioxidants in composite systems [20]
Systematic investigation of Thai FDA certified medicinal plant extracts revealed that *Bacopa monnieri, Camellia sinensis, Coffea arabica, Curcuma longa, Tagetes erecta and Terminalia chebula* could be sources of useful constituents. These standard extracts showed high phenolics (up to 1378 mg GAE/g), flavonoids and strong metal chelating and free radical scavenging properties, highlighting their potential in functional meals for delay of neurodegenerative illnesses and other oxidative stress-related ailments [21].

2 Mechanisms of Antioxidant Action in Food Systems

2.1 Radical scavenging and redox modulation

Plant-based antioxidants primarily protect foods by scavenging reactive oxygen species and lipid free radicals interfering with chain propagation mechanisms driving lipid peroxidation. Phenolic compounds give hydrogen atoms or electrons from their hydroxyl groups to radicals such as peroxyl (ROO·), which form more stable phenoxy radicals that can be delocalized through resonance of aromatic rings. This redox behaviour is the reason for the high activity in in vitro experiments such as DPPH and ABTS radical scavenging, FRAP reducing power, and ORAC peroxyl radical absorbance [22] Fig 4. There have been several studies of positive association between TPC and antioxidant properties of plant extracts, which highlight the importance of phenolic content as an indicator of functional performance for foods. However, the phenolics' structure (number of hydroxyl groups, their conjugation, glycosides or other substituents) also influences reactivity, and further profiling is needed beyond bulk TPC [23].

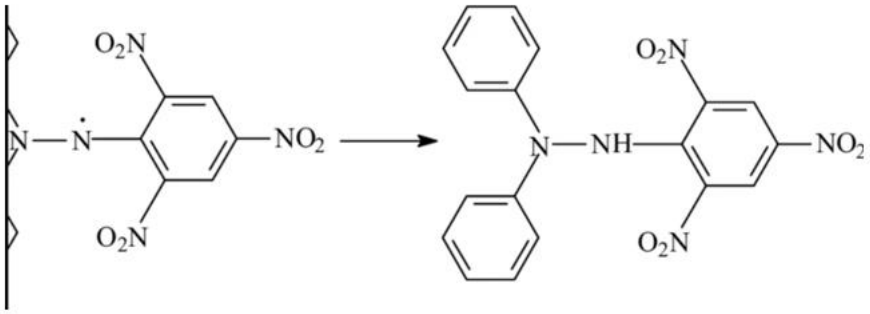

Figure 4. Free radical scavenging activity of DPPH (adapted from Brand-Williams et al., 1995).

2.2 Metal chelation and pro-oxidant control

Metals like iron and copper can catalyze the formation of highly reactive hydroxyl radicals by means of Fenton and Haber-Weiss mechanisms, hence increasing the oxidation rate in foods. Many phenolic compounds can chelate metal ions through catechol or galloyl groups (e.g. Fe^{2+} and Cu^{2+}) and hence limit their catalytic activity. This is particularly true for meat products, emulsions, and fortified foods where metal contamination or intentional fortification is common. The typical medicinal plant extracts with a high phenolic and flavonoid content have exhibited good metal-chelating and radical-scavenging activities and therefore have the potential to be very effective antioxidants once used as a plant product. The balance between metal chelation and potential pro-oxidant behaviour (e.g., redox cycling in some circumstances) should be considered, especially at high concentrations or in the presence of transition metals [25].

2.3 Physical barrier effects and active packaging

Plant-based antioxidants can be embedded in films, coatings and structured matrices and can have physical barrier and chemical scavenging effects. Edible films and coatings containing plant extract or essential oils or phenolic-rich fractions decrease oxygen permeability, moisture exchange and direct contact with pro-oxidant species at the food-environment interface. For instance, cellulose-based membranes containing pomegranate seed extract and rosemary or aloe vera essential oils have antioxidant activity, reduced swelling, modified mechanical properties and reduced lipid oxidation in contact foods [25]. Active packaging systems like chitosan films or nanoemulsions with plant essential oils in addition to shelf life and safety also block fungal growth (e.g. Aspergillus flavus) in stored food. They also demonstrate that plant-based functional ingredients in such systems can be put into food and packaging materials, too, not only for food, but also to preserve products and keep them safe in the long run [26].

3 Technological Strategies for Incorporating Plant Antioxidants

3.1 Direct addition of extracts, powders, and concentrates

The most straightforward approach is direct fortification of food using plant extracts, juices, powders or concentrates, either alone or in combination. This approach is common in beverages, dairy products, bakery items, meat products, and snack foods. The consumption of polyphenol-rich fruit juices, red wine, chocolate and berry preparations have been shown to improve systemic antioxidant status and lower oxidative damage. Turning those findings into functional foods is to balance antioxidant enrichment with appropriate sensory profiles. As an example of the combination approach, yogurt fortified with microencapsulated fish protein

hydrolysates or plant polyphenols showed increased antioxidant and antihypertensive activity and tasted good as well in storage. Tomato-based snack bars with plant proteins enhanced antioxidant activity and also had anti-obesity, anti-inflammatory and anti-diabetic effects and demonstrated that multi-component plant-based formulations may address oxidative stress and metabolic risk factors at once [27].

3.2 Microencapsulation of plant antioxidants

Microencapsulation is widely used to protect labile plant antioxidants from degradation, mask unwanted sensory properties and control release profiles. Spray drying, freeze-drying, coacervation, liposome formation, ionic gelation, solvent evaporation are some of the techniques used for this purpose. Protein (whey protein, gelatin), polysaccharides (maltodextrin, gum Arabic), lipids and inorganic materials are

used for encapsulation in food applications [28]. The review of microencapsulation with food antioxidants indicated that physical techniques such as spray drying and lyophilisation are widely used in the food industry for scalability. In contrast, physicochemical approaches like coacervation and liposomes allow for control of particle size and release properties. The encapsulation of flavonoids from yellow onion skins in whey protein isolate–xylose Maillard conjugates resulted in 90% encapsulation efficiencies and adding these microcapsules to nachos greatly increased the antioxidant value of the product. Such approaches highlight how phenolic-rich by-products are being regarded as microencapsulated components of snack food [29].

3.3 Nanoencapsulation and nanoscale delivery systems

Nano-gels, nanoliposomes, solid lipid nanoparticles, polymeric nanoparticles and nanoemulsions have increased surface area, solubility and dispersibility, and can be released and delivered to plants as well. These are quite useful for lipophilic compounds such as carotenoids and certain flavonoids that have low water solubility and low bioavailability in their original plant form. A review of a number of plant-derived, nanoscale-encapsulated antioxidants showed that nanoencapsulation improved stability, retention, and bioaccessibility of β-carotene, lycopene, quercetin, rutin, myricetin and resveratrol [30]. For example, the β-carotene-loaded high-internal-phase emulsion gels had high gel network density and antioxidant capacity and retained β-carotene in simulated gastrointestinal conditions as opposed to non-structured emulsions. And nanoemulsions of lycopene and kaempferol showed better permeation and deposition, skin accumulation, as well as oral bioavailability compared to non-encapsulated ones [31].

3.4 Cyclodextrin inclusion complexes and coacervation

In this context, encapsulation of polyphenols with cyclodextrins and coacervates with oppositely charged biopolymers (gelatin and pectin) are other ways to enhance their stability and bioavailability. In the case of taxifolin, a flavonoid with excellent antioxidant activity, encapsulation in β-cyclodextrin or gelatin-pectin

coacervates was found to have a small decrease in the in vitro antioxidant capacity (around 19-25%) but very high bioactivity indices and protection of the cell in a simulated manner [32]. The bioactivity of the encapsulated taxifolin was 72-87% compared to 51% for the non-encapsulated taxifolin, indicating the importance of encapsulation in maintaining functional performance even at low assay-level losses. This is a clear indication that encapsulation is needed in the field of plant antioxidants and for health protection and not just for food stability [33].

4. Applications in Specific Food Systems

4.1 Dairy and fermented products

Dairy products including yogurt and fermented milk are commonly consumed and can be used as a diverse source of hydrophilic and lipophilic plant antioxidants. Protein hydrolysates, polyphenols, and carotenoids have been successfully added to yogurts for antioxidant and antihypertensive or metabolic activities and at the same time, still taste good. For instance, when fish protein hydrolysate microcapsules were added to yogurt, it was found that the antioxidants and ACE-inhibitory activity were increased over a 7-day storage period, and the taste and texture were satisfactory. In addition, Tamarillo polyphenols were added

to yogurt, which were used in cubosomal systems for better physicochemical and nutritional effects, which indicates that a better delivery system is also possible for dairy-based functional foods [34].

4.2 Bakery and cereal-based products

Bakery and cereal products (breads, biscuits, snack bars etc.) are prone to lipid oxidation because of fat and high processing temperature. Plant-based antioxidants can be used to enhance oxidative stability and have other health benefits in terms of antioxidant activity and fiber intake. Experiments proved that plant protein-based snack bars containing tomato have higher antioxidant, anti-obesity and anti-inflammatory effects, showing that well-designed formulations can encompass many health endpoints in a single product. Phenolic-rich by-product flours (such as grape pomace, cereal brans) have also been investigated in bakery products but texture, color, and taste of the product should be considered with recipe optimization and consumer testing [35].

4.3 Beverages and liquid food

Fruit juices, teas, coffees, and functional drinks are natural carriers for hydrophilic plant antioxidants and have been widely studied in epidemiological and intervention studies. Short-term consumption of polyphenol-rich fruit juices, red wine, chocolate, and berry-based preparations, on the other hand, has been associated with enhanced plasma antioxidant status and reduced biomarkers of oxidative damage. Functional beverages can also be fortified with standardized medicinal plant extracts that are selected for health benefits (e.g. neuroprotection or metabolic regulation). The use of standardized plant extracts with high phenolic and flavonoid content (for example, *Curcuma longa, Camellia sinensis, or Coffea arabica*) has shown to be highly metal-chelating and radical scavenging and is therefore effective in beverages to delay the onset of neurodegenerative disease. However, stability and solubility issues and sensory effects, such as bitterness and astringency, have to be taken into account when formulating and (sometimes) flavor-masking [36,37].

4.4 Meat and fat dense foods

Meat products and other lipid rich meals are especially sensitive to oxidative rancidity resulting in off-odours, color changes and nutritional loss. The plant-based antioxidants from herbs, spices and medicinal plants are emerging as natural preservatives in such systems. Phenolic-rich extracts from oregano, rosemary, and other *Laminaceae* have demonstrated radical scavenging and metal-chelating activity. They can significantly reduce lipid oxidation in meat products. It has been found that plant extracts can also outperform traditional synthetic antioxidants in the treatment of lipid oxidation and can have other functional properties - for instance, antimicrobial ability. At the same time, high concentrations of plant extracts can impact colour and taste, hence concentration, processing and ingredients need to be adjusted to provide protection and sensory acceptance [38, 39].

4.5 Edible films, coatings and active packaging with plant-based antioxidants: a supplementary method to food fortification.

Cellulose-based films with pomegranate seed extract and essential oils (rosemary, aloe vera) demonstrated robust antioxidant activity, reduced swelling, and modified tensile properties, thereby reducing lipid oxidation in the food products they were in contact with. Nanoencapsulation of essential oils, such as Ocimum odorata, in chitosan-based nanoemulsions inhibited the growth of Aspergillus flavus, enhanced

antioxidant activity, and prevented aflatoxin production and lipid peroxidation in stored food. The examples provided demonstrate the employment of functional chemicals obtained from plants in packaging strategies to provide local and sustained distribution of antimicrobials and antioxidants to improve food safety and shelf-life [40,41].

5 Factors Influencing Antioxidant Effectiveness in Foods

5.1 Food matrix interactions and processing conditions.

The level of plant-based antioxidants in food is heavily affected by the composition and structure of the food matrix (i.e., pH, water activity, lipid content, emulsifiers and pro-oxidant metals). The interaction of proteins and polysaccharides may influence the partition of phenolics in aqueous and lipid phases, which may mean that they are not available at critical sites of oxidation. For instance, in emulsions, the position of antioxidants at the oil-water interface is very important for protection. Processing conditions (pasteurization, baking, drying, and exposure to light and oxygen) can lead to degradation, isomerization, or polymerization of phenolics and carotenoids and hence to changes in antioxidant activity. With appropriate carrier materials, encapsulation in appropriate carrier materials is one way to minimize processing-induced losses by providing protective microenvironments, but formulation and process parameters must be tailored for each system differently [42, 43]

5.2 Bioavailability and in vivo relevance

While plant extracts have very high antioxidant activity in vitro and in vivo their health benefits depend on absorption, metabolism, distribution, and excretion as well as their ability to alter endogenous antioxidant pathways in vivo [44]. Polyphenols undergo extensive metabolism in the gut and liver, and the resulting conjugated product can produce a series of metabolites which can have different antioxidant activity from its parent compounds in the body; hence, the in vitro action does not necessarily translate to strong in vivo effects. Envelopment and delivery methods that promote solubility, shields compounds from degradation, and allow controlled release that can improve bioavailability and functional outcomes. Studies on encapsulated taxifolin, β-carotene, and other flavonoids have shown that nano- and microencapsulated forms have higher bioactivity and better antioxidant activity in simulated gastrointestinal conditions than non-encapsulated ones, even though the initial in vitro antioxidant capacity can be lower. This highlights the need to consider biological and technological criteria when deciding how to use plant-based functional ingredients and how well they are tolerated in the market [45].

The use of plant extracts and concentrates can be limited in highly flavored goods, especially at high inclusion levels, due to bitterness, astringency, rich color and characteristic odors. Encapsulation can be a strong strategy for masking unpleasant tastes and odours, regulating release and minimizing visual impact but can increase formulation complexity and cost. Sensory effects and functional qualities can also be managed by using certain plant sections, extract quality or standardized fractions. Natural antioxidants are generally better accepted in general than synthetic ones, especially in the context of plant-based diets and clean labels and minimally processed foods. But acceptance is ultimately based on the quality of the sensory experience, health benefits, and price of the final product. Transparency in terms of health claims and the use of special functional ingredients and technology are important to communicate the value of the product and to justify the use of a specific functional material [46].

6 Sustainability and circular economy perspectives

Plant-based functional ingredients Table 1, have been linked closely to circular economy principles especially when antioxidants are recovered from agri-food by-products and waste streams like peels, pomace, seeds and leaves. Recent studies have demonstrated remarkable antioxidant activity in potato peel, beetroot peel, onion skin and other residues, indicating that these materials are cheap and sustainable sources of natural antioxidants for food applications [47]. Micro- and nanoencapsulation of bioactive compounds from plant by-products can also help with stability, controlled release to be added to various food matrices and thereby increase the value of these underutilised resources. In the food industry, the incorporation of these products in edible films, coatings, and active packaging systems made of biodegradable polymers, on the other hand, is also further enhancing the sustainability benefits and avoids the dependency on synthetic preservatives and conventional plastics. From a systems perspective, the biorefinery approach that sequentially extracts high-value antioxidants, dietary fibres and other components from plant wastes can open up food and packaging lines to closing loops and increase the sustainability of agriculture and the food sector [48].

Table 1 List of Bioactive compounds

S.NO.	Name of the compound	Class/Category	Source	Reference
1	**Taxifolin (Dihydroquercetin)**	Flavonoid	Onions, milk thistle, Siberian larch, Douglas fir bark	Mandour et al. (2026)
2	**Lutein**	Carotenoid (xanthophyll)	Leafy greens (spinach, kale), egg yolk, marigold flowers	Johra et al. (2020)
3	**Zeaxanthin**	Carotenoid (xanthophyll)	Corn, orange peppers, leafy greens, egg yolk	Johra et al. (2020)
4	**β-Carotene**	Carotenoid (carotene)	Carrots, sweet potato, pumpkin, mango	Johra et al. (2020)
5	**Lycopene**	Carotenoid (carotene)	Tomato (and tomato peel/pomace), watermelon, pink guava	Kumar et al. (2023)
6	**Polyphenols (general)**	Phenolic compound	Fruits, vegetables, tea, coffee, cocoa, wine	Scalbert et al. (2005)
7	**Tea Polyphenols (Catechins)**	Flavonoid / Phenolic	Green tea, black tea (*Camellia sinensis*)	Khan & Mukhtar (2007)
8	**Flavonoids (general, e.g., Cruciata taurica)**	Flavonoid	Cruciata taurica and related medicinal plants	Zengin et al. (2020)
9	**Alkaloids (e.g.,Vincristine/ Vinblastine precursors)**	Alkaloid	Catharanthus roseus (Madagascar periwinkle)	McEvoy et al. (2011)

10	**Betalains**	Natural colorant / Nitrogenous pigment	Beetroot, red dragon fruit, amaranth, Swiss chard	Abedi-Firoozjah et al. (2023)
11	**Algal Bioactive Compounds**	Mixed (pigments, polysaccharides, peptides)	Marine and freshwater algae (e.g., *Spirulina, Chlorella*)	Bouafir et al. (2025)
12	**Bioactive Plant Peptides**	Peptide	Legume seeds, cereal grains, plant protein hydrolysates	Avilés-Gaxiola et al. (2025)
13	**Bioactive Polysaccharides**	Polysaccharide	Plant cell walls, seaweeds, mushrooms, seeds	Salehi & Rashidinejad (2025)
14	**Edible Flower Bioactives**	Mixed (phenolics, flavonoids)	Edible flowers *(*rose, chrysanthemum, hibiscus, etc.)	Afzaal et al. (2025)
15	**Rose (Rosa hybrida) Antioxidants**	Phenolic / Anthocyanin	Rose petals (Rosa hybrida cultivars)	Yang & Shin (2017); Vinokur et al. (2006)
16	**Chrysanthemum –Wolfberry Combination Compounds**	Mixed (flavonoids, carotenoids)	Chrysanthemum morifolium flowers and *Lycium barbarum* (wolfberry) fruit	Zhang et al. (2019)
17	**Bacterial Pigments**	Pigment (carotenoid/melanin-type)	Pigment-producing bacteria (e.g., Serratia, Rhodobacter)	Agarwal et al. (2023)
18	**Soy Leghemoglobin**	Heme protein	Soybean root nodules (Glycine max)	Ahmad et al. (2023)
19	**Carotenoids & Chlorophylls (Krill Oil)**	Carotenoid / Chlorophyll	Antarctic krill (Euphausia superba) oil	Abad & Shahidi (2026)
20	**Phytochelatins / Metal-Chelating Compounds**	Peptide / Chelator	Tropical medicinal plants (various species)	Kumar et al. ()
21	**DPPH (Reference radical for antioxidant assay)**	Assay reagent (methodological reference)	Synthetic stable free radical (2,2-diphenyl-1-picrylhydrazyl) — not plant-derived	Brand-Williams et al. (1995)

7 Research Gaps and Future Directions

Despite the extensive research on this field, there is still a lack of scientific and technological knowledge on plant-based functional ingredients to enhance antioxidant activity in food. First, there are no standardized methods to assess antioxidant activity in complex food systems and in vitro assay as results

cannot be compared with in vivo health outcomes. Different extraction protocols, assay conditions, and reporting units make cross-study comparisons difficult and lack a single standardization of formulation and labeling. Testing methods in the matrix and multi-parameter assessment frameworks need to be standardized and tested. Second, more work is needed to understand structure-function relationships between specific phenolic structures, conjugation patterns, and delivery system architectures and antioxidant performance in foods and biological systems. Advanced analysis techniques, omics approaches, and mechanistic studies can now help to better understand the structural features and interactions that drive functionality, thus enabling a much more informed decision-making process for ingredients and preparations. Third, nano- and microencapsulation are promising tools for improving stability and bioavailability, but further research is required on the safety and regulatory aspects, scale-up, and cost-effectiveness of such technologies in real-life food production. The integration of individual variability, gut microbiota interactions, and dietary habits will be vital to move towards personalized functional nutrition in the future [49].

8 Conclusions

Plant-based functional ingredients are a variety of different and versatile tools to enhance antioxidant potential in food systems. Their mechanisms of action (radical scavenging, metal chelation, redox modulation, and physical barrier effect) can help to slow oxidative deterioration of food and help to alleviate oxidative stress in humans These challenges will enable the rational design of next-generation functional foods that utilize plant-based functional ingredients to generate technological and health benefits in a sustainable manner [50].

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10 Conflict of interest

The author declares that there is no conflict of interest regarding the publication of this research.

REFERENCES:

1. Cotabarren, J., Ozon, B., Claver, S., Garcia-Pardo, J., & Obregon, W. D. (2021). Purification and identification of novel antioxidant peptides isolated from *Geoffroea decorticans* seeds with anticoagulant activity. *Pharmaceutics, 13*, 1153. https://doi.org/10.3390/pharmaceutics13081153
2. Vildanova, M., Vishnyakova, P., Saidova, A., Konduktorova, V., Onishchenko, G., & Smirnova, E. (2021). Gibberellic acid initiates ER stress and activation of differentiation in cultured human immortalized keratinocytes HaCaT and epidermoid carcinoma cells A431. *Pharmaceutics, 13*, 1813. https://doi.org/10.3390/pharmaceutics13111813
3. Abdalla, M. A., Li, F., Wenzel-Storjohann, A., Sulieman, S., Tasdemir, D., & Mühling, K. H. (2021). Comparative metabolite profile, biological activity and overall quality of three lettuce (*Lactuca sativa* L., Asteraceae) cultivars in response to sulfur nutrition. *Pharmaceutics, 13*, 713. https://doi.org/10.3390/pharmaceutics13050713

4. Wikan, N., Hankittichai, P., Thaklaewphan, P., Potikanond, S., & Nimlamool, W. (2022). Oxyresveratrol inhibits TNF-α-stimulated cell proliferation in human immortalized keratinocytes (HaCaT) by suppressing AKT activation. *Pharmaceutics, 14*, 63. https://doi.org/10.3390/pharmaceutics14010063
5. Sasidharan, S., Chen, Y., Saravanan, D., et al. (2011). Extraction, isolation and characterization of bioactive compounds from plants' extracts. *African Journal of Traditional, Complementary and Alternative Medicines, 8*(1), 1–10.
6. Zengin, G., Sarikurkcu, C., & Aktumsek, A. (2020). Phenolic constituents, antioxidant and enzyme inhibitory activities of *Cruciata taurica* endemic to Turkey. *Chemistry & Biodiversity, 17*(2), e1900506.
7. Scalbert, A., Johnson, I. T., & Saltmarsh, M. (2005). Polyphenols: Antioxidants and beyond. *The American Journal of Clinical Nutrition, 81*(1), 215S–217S.
8. Khan, N., & Mukhtar, H. (2007). Tea polyphenols for health promotion. *Life Sciences, 81*(7), 519–533.
9. McEvoy, C. R., Naveen, M., Abhilash, M., et al. (2011). Pharmacognostic and phytochemical studies of *Catharanthus roseus* Linn. *International Journal of Pharmaceutical Sciences and Research, 2*(6), 1411–1416.
10. Abad, A., & Shahidi, F. (2026). Carotenoids and chlorophylls in antarctic krill (*Euphausia superba*) oil. *Food Bioscience*, Article 108270.
11. Abedi-Firoozjah, R., Parandi, E., Heydari, M., Kolahdouz-Nasiri, A., Bahraminejad, M., Mohammadi, R., Garavand, F. (2023). Betalains as promising natural colorants in smart/active food packaging. *Food Chemistry, 424*, Article 136408.
12. Agarwal, H., Bajpai, S., Mishra, A., Kohli, I., Varma, A., Fouillaud, M., ... Joshi, N. C. (2023). Bacterial pigments and their multifaceted roles in contemporary biotechnology and pharmacological applications. *Microorganisms, 11*(3), 614.
13. Ahmad, M. I., Farooq, S., Alhamoud, Y., Li, C., & Zhang, H. (2023). Soy leghemoglobin: A review of its structure, production, safety aspects, and food applications. *Trends in Food Science & Technology, 141*, Article 104199.
14. Johra, F. T., Bepari, A. K., Bristy, A. T., & Reza, H. M. (2020). A Mechanistic Review of β-Carotene, Lutein, and Zeaxanthin in Eye Health and Disease. *Antioxidants, 9*(11), 1046. https://doi.org/10.3390/antiox9111046
15. Brand-Williams, W., Cuvelier, M. E., & Berset, C. (1995). Use of a free radical method to evaluate antioxidant activity. LWT - Food Science and Technology, 28(1), 25–30.
16. Castro, M. L., Ferreira, J. P., Pintado, M., Ramos, O. L., Borges, S., & Baptista-Silva, S. (2023). Grape by-products in sustainable cosmetics: Nanoencapsulation and market trends. *Applied Sciences, 13*(16), 9168.
17. Cazón, P., & Silva, A. S. (2024). Natural pigments from food wastes: New approaches for the extraction and encapsulation. *Current Opinion in Green and Sustainable Chemistry*, Article 100929.
18. Bouafir, Y., Bouhenna, M. M., Nebbak, A., Belfarhi, L., Aouzal, B., Boufahja, F., & Bruno, M. (2025). Algal bioactive compounds: A review on their characteristics and medicinal properties. *Fitoterapia, 183*, Article 106591. https://doi.org/10.1016/j.fitote.2025.106591

19. Avilés-Gaxiola, S., García-Aguiar, I., Jiménez-Ortega, L. A., Gutiérrez-Grijalva, E. P., & Heredia, J. B. (2025). Bioactive plant peptides: Physicochemical features, structure-function insights and mechanism of action. *Molecules, 30*(18), 3683. https://doi.org/10.3390/molecules30183683
20. Salehi, M., & Rashidinejad, A. (2025). Multifaceted roles of plant-derived bioactive polysaccharides: A review of their biological functions, delivery, bioavailability, and applications within the food and pharmaceutical sectors. *International Journal of Biological Macromolecules, 290*, Article 138855. https://doi.org/10.1016/j.ijbiomac.2024.138855
21. Afzaal, M., et al. (2025). Bioactive compounds and therapeutic potential of edible flowers. In A. Poonia, P. S. Panesar, & M. I. Moreno (Eds.), *Edible flowers: Source of phytonutrients, valorization and technological advancements* (Ch. 7). Springer. https://doi.org/10.1007/978-3-032-00667-7_7
22. Zhang, N., He, Z., He, S., & Jing, P. (2019). Insights into the importance of dietary chrysanthemum flower (*Chrysanthemum morifolium* cv. Hangju)–wolfberry (*Lycium barbarum* fruit) combination in antioxidant and anti-inflammatory properties. *Food Research International, 116*, 810–818.
23. Yang, H., & Shin, Y. (2017). Antioxidant compounds and activities of edible roses (*Rosa hybrida* spp.) from different cultivars grown in Korea. *Applied Biological Chemistry, 60*(2), 129–136.
24. Vinokur, Y., Rodov, V., Reznick, N., Goldman, G., Horev, B., Umiel, N., & Friedman, H. (2006). Rose petal tea as an antioxidant-rich beverage: Cultivar effects. *Journal of Food Science, 71*(1), S42–S47.
25. *[Incomplete — only "www.storage.googlespis.com" was given; please provide the full source]*
26. Sharma, N., Negi, N., Kaur, H., et al. (2025). Metabolic adaptations in plants: Navigating heavy metal stress for sustainable plant growth. *Discover Applied Sciences, 7*, 1041. https://doi.org/10.1007/s42452-025-06715-w
27. Kumar, S., et al. (n.d.). Antioxidant, metal chelating, anti-glucosidase activities and phytochemical analysis of selected tropical medicinal plants. *PMC*. https://pmc.ncbi.nlm.nih.gov/articles/PMC4232808/
28. Dahiya, D., Terpou, A., Dasenaki, M., & Nigam, P. S. (2023). Current status and future prospects of bioactive molecules delivered through sustainable encapsulation techniques for food fortification. *Sustainable Food Technology, 1*(4), 500–510. https://doi.org/10.1039/D3FB00015J
29. Devi, N., Sarmah, M., Khatun, B., & Maji, T. K. (2017). Encapsulation of active ingredients in polysaccharide–protein complex coacervates. *Advances in Colloid and Interface Science, 239*, 136–145. https://doi.org/10.1016/j.cis.2016.05.009
30. Aguiar, J., Estevinho, B. N., & Santos, L. (2016). Microencapsulation of natural antioxidants for food application – The specific case of coffee antioxidants – A review. *Trends in Food Science & Technology, 58*, 21–39. https://doi.org/10.1016/j.tifs.2016.10.012
31. Jia, Z., Dumont, M.-J., & Orsat, V. (2016). Encapsulation of phenolic compounds present in plants using protein matrices. *Food Bioscience, 15*, 87–104. https://doi.org/10.1016/j.fbio.2016.05.007
32. de Souza Simões, L., Madalena, D. A., Pinheiro, A. C., Teixeira, J. A., Vicente, A. A., & Ramos, O. L. (2017). Micro- and nano bio-based delivery systems for food applications: In vitro behavior. *Advances in Colloid and Interface Science, 243*, 23–45. https://doi.org/10.1016/j.cis.2017.02.010
33. Hu, H., & Xu, F.-J. (2020). Rational design and latest advances of polysaccharide-based hydrogels for wound healing. *Biomaterials Science, 8*(8), 2084–2101. https://doi.org/10.1039/D0BM00055H

34. Mandour, G. H., El-Dessouki, A. M., Attallah, K. A., Seliem, M. A., Abdullah, A. R., Khidr, E. G., El-Husseiny, A. A., El-Shiekh, R. A., Hafez, M. M., & Khalifa, H. O. (2026). Exploring the therapeutic potential of naturally occurring taxifolin, a dietary flavonoid: An updated comprehensive review. *Frontiers in Pharmacology, 17*, Article 1780792. https://doi.org/10.3389/fphar.2026.1780792
35. Gruskiene, R., Bockuviene, A., & Sereikaite, J. (2021). Microencapsulation of bioactive ingredients for their delivery into fermented milk products: A review. *Molecules, 26*(15), 4601. https://doi.org/10.3390/molecules26154601
36. Tolve, R., Bianchi, F., Lomuscio, E., Sportiello, L., & Simonato, B. (2023). Current advantages in the application of microencapsulation in functional bread development. *Foods, 12*(1), 96. https://doi.org/10.3390/foods12010096
37. Gupta, A., Sanwal, N., Bareen, M. A., Barua, S., Sharma, N., Olatunji, O. J., Nirmal, N. P., & Sahu, J. K. (2023). Trends in functional beverages: Functional ingredients, processing technologies, stability, health benefits, and consumer perspective. *Food Research International, 170*, Article 113046. https://doi.org/10.1016/j.foodres.2023.113046.
38. Artés-Hernández, F., Castillejo, N., Martínez-Zamora, L., & Martínez-Hernández, G. B. (2021). Phytochemical fortification in fruit and vegetable beverages with green technologies. *Foods, 10*(11), 2534. https://doi.org/10.3390/foods10112534
39. Olvera-Aguirre, G., Piñeiro-Vázquez, Á. T., Sanginés-García, J. R., Sánchez Zárate, A., Ochoa-Flores, A. A., Segura-Campos, M. R., Vargas-Bello-Pérez, E., & Chay-Canul, A. J. (2023). Using plant-based compounds as preservatives for meat products: A review. *Heliyon, 9*(6), e17071. https://doi.org/10.1016/j.heliyon.2023.e17071
40. Šojić, B., Milošević, S., Savanović, D., Zeković, Z., Tomović, V., & Pavlić, B. (2023). Isolation, bioactive potential, and application of essential oils and terpenoid-rich extracts as effective antioxidant and antimicrobial agents in meat and meat products. *Molecules, 28*(5), 2293. https://doi.org/10.3390/molecules28052293
41. Nogueira, G. F., de Oliveira, R. A., Velasco, J. I., & Fakhouri, F. M. (2020). Methods of incorporating plant-derived bioactive compounds into films made with agro-based polymers for application as food packaging: A brief review. *Polymers, 12*(11), 2518. https://doi.org/10.3390/polym12112518
42. Bioactive edible films for food applications: Influence of the bioactive compounds on film structure and properties. *Critical Reviews in Food Science and Nutrition, 59*(7). https://doi.org/10.1080/10408398.2017.1393384
43. Food matrix effects on plant-derived bioactive compounds and micronutrients: Implications for functional food development. (2026). *International Journal of Molecular Sciences, 27*(12), 5503. https://doi.org/10.3390/ijms27125503
44. Mishra, A. K., Singh, R., Rawat, H., Kumar, V., Jagtap, C., & Jain, A. (2024). The influence of food matrix on the stability and bioavailability of phytochemicals: A comprehensive review. *Food and Humanity, 2*, Article 100202. https://doi.org/10.1016/j.foohum.2023.100202
45. Shahidi, F., & Pan, Y. (2021). Influence of food matrix and food processing on the chemical interaction and bioaccessibility of dietary phytochemicals: A review. *Critical Reviews in Food Science and Nutrition, 62*(23), 6421–6445. https://doi.org/10.1080/10408398.2021.1901650

46. Udenigwe, C. C., & Fogliano, V. (2017). Food matrix interaction and bioavailability of bioactive peptides: Two faces of the same coin? *Journal of Functional Foods, 35*, 9–12. https://doi.org/10.1016/j.jff.2017.05.029
47. Li, J., Zhu, H., Yuan, X., Ji, J., Ren, J., Liao, M., Först, P., Chen, F., Liu, Y., Hu, X., & Ma, L. (2026). Engineered food matrix: Precision processing strategies to enhance bioavailability of bioactive phytochemicals. *Comprehensive Reviews in Food Science and Food Safety, 25*(3), e70454. https://doi.org/10.1111/1541-4337.70454
48. Kumar, S., Rawson, A., Kumar, A., Ck, S., Vignesh, S., & Venkatachalapathy, N. (2023). Lycopene extraction from industrial tomato processing waste using emerging technologies, and its application in enriched beverage development. *International Journal of Food Science and Technology, 58*(4), 2141–2150. https://doi.org/10.1111/ijfs.16156
49. Bio-sourcing from byproducts: A comprehensive review of bioactive molecules in Agri-Food Waste (AFW) streams for valorization and sustainable applications. (2025). *Bioresource Technology*. https://www.sciencedirect.com/science/article/abs/pii/S0960852425006066
50. Bekavac, N., Krog, K., Stanić, A., Šamec, D., Šalić, A., Benković, M., Jurina, T., Gajdoš Kljusurić, J., Valinger, D., & Jurinjak Tušek, A. (2025). Valorization of food waste: Extracting bioactive compounds for sustainable health and environmental solutions. *Antioxidants, 14*(6), 714. https://doi.org/10.3390/antiox14060714
51. Karmakar, R., Aggarwal, S., Kathuria, D., Singh, N., Tripathi, V., Sharma, P. K., Mitra, D., Kumar, S., & Bhattacharya, S. (2025). Valorization of food waste stream by harnessing bioactive compounds: A comprehensive review on the process, challenges and solutions. *Food Bioscience, 69*, Article 106833. https://doi.org/10.1016/j.fbio.2025.106833