

Functional soups as food matrices for bioactive compounds: Implications for cognitive health

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Abstract: Nutritional strategies supporting healthy ageing and cognitive well-being have gained increasing attention as global populations age. Among dietary approaches, foods rich in bioactive compounds are of particular interest due to their potential involvement in biological pathways relevant to cognitive function. Soups represent versatile food matrices for incorporating and delivering a wide range of plant-derived ingredients, including vegetables, legumes, herbs, and mushrooms. These ingredients provide bioactive compounds such as polyphenols, carotenoids, terpenoids, dietary fibre, and other phytochemicals exhibiting antioxidant, anti-inflammatory, and enzyme-modulating properties. Evidence from nutritional, experimental, and mechanistic studies suggests that such compounds may influence processes associated with cognitive health, including oxidative balance, inflammatory responses, and gut–brain axis interactions. In addition, food-processing technologies such as pulsed electric fields and high hydrostatic pressure may improve the retention and bioaccessibility of selected bioactive compounds in soup-based foods. However, direct evidence linking soup consumption with cognitive outcomes remains limited, and much of the available literature is derived from studies on individual ingredients, isolated compounds, or experimental models. This review critically examines the role of soups as functional food matrices for the delivery of bioactive compounds associated with cognitive health, rather than as independently proven neuroprotective interventions. Particular attention is given to distinguishing direct soup-based evidence from ingredient-based and mechanistic studies, while also discussing the influence of technological processing on bioactive compound stability, bioaccessibility, and the potential nutritional value of functional soup formulations.

Keywords: bioaccessibility; food processing; thermal stability; phytochemicals; plant-based ingredients; food formulation

Functional foods and nutraceuticals have emerged as a rapidly expanding field at the interface of food science, nutrition, and public health. While nutraceuticals are commonly defined as isolated bioactive compounds or concentrated preparations providing health benefits

beyond basic nutrition, functional foods deliver such bioactives within natural or minimally processed food matrices, enabling regular dietary intake and improved consumer compliance (DeFelice 1995; Keservani et al. 2010; Puri et al. 2022). In the context of global de-

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mographic shifts, particularly the progressive ageing of populations, preventive nutritional strategies have gained increasing importance as non-pharmacological tools to support long-term health, delay functional decline, and reduce the burden of chronic diseases, including neurodegenerative disorders such as Alzheimer's disease (AD) (Fekete et al. 2025). Among emerging targets of preventive nutrition, cognition has received growing scientific attention. Cognition encompasses multiple interrelated domains, including memory, attention, learning capacity, and executive functions such as planning, decision-making and cognitive flexibility. These functions are essential for maintaining independence and quality of life across the lifespan. Age-related cognitive decline and neurodegenerative diseases, such as AD, are strongly associated with chronic low-grade neuroinflammation, oxidative stress, impaired cholinergic neurotransmission and dysregulation of the gut–brain axis (Heneka et al. 2015; Ammar et al. 2020; Prakash and Verma 2024). Accumulating evidence indicates that diet plays an important role in maintaining healthy brain ageing through complex interactions involving antioxidant and anti-inflammatory nutrients, gut microbiota, and metabolic homeostasis. Within this context, soups represent versatile food matrices rather than simply sources of individual bioactive compounds. Their semi-liquid structure, compositional flexibility, and broad cultural acceptance allow the incorporation of a wide range of plant-based ingredients while providing a practical vehicle for the dietary delivery of bioactive compounds. From a technological perspective, soup matrices facilitate the combination of vegetables, legumes, herbs, mushrooms, and other functional ingredients into a single food product (Fernández-López et al. 2020). Their high water content, soft texture, and relatively low energy density make them particularly suitable for older adults and individuals with reduced chewing capacity or appetite. In addition, technological processing applied during soup preparation may improve the stability and bioaccessibility of selected compounds, including carotenoids and matrix-bound polyphenols, by modifying plant cell structures and enhancing their release during gastrointestinal digestion (Călinoiu and Vodnar 2019; Holland et al. 2020).

For the purposes of this review, all available studies addressing the impact of soup consumption on cognitive outcomes and diseases associated with metabolic syndrome were included, although such studies are relatively scarce. On the other hand, evidence regarding the ingredients used in soups indirectly suggests

their potential relevance to the prevention of these diseases. Therefore, the aim of this review is not to evaluate functional soups as independently proven neuroprotective interventions, but rather to examine their role as food matrices for the delivery of bioactive compounds associated with cognitive health. Accordingly, the review integrates evidence from direct soup-based studies, ingredient-based research, and mechanistic investigations, while critically distinguishing between these levels of evidence and highlighting the influence of technological processing, bioaccessibility, and formulation on the potential health value of functional soups.

Cultural importance and dietary acceptance of soups. Globally, soups have a deep cultural history and archaeological evidence indicates that soup consumption dates back as far as 20 000 B.C. in China (Wu et al. 2012). In other countries, soups have been present for centuries, as an integral part of the daily diet. In Poland, traditional varieties such as *krupnik*, *zurek*, *barszcz*, and vegetable broths are consumed regularly. Detailed national dietary surveys include soups as a separate mixed-dish category, and frequency-of-intake data confirm that both urban and rural populations consume soups every day, whereas powdered soups are eaten relatively infrequently (Stoś et al. 2021). Soup consumption is also associated with better diet quality among U.S. adults (Zhu and Hollis 2014). In summary, the widespread cultural acceptance of soups provides opportunities to incorporate a variety of nutrient-rich and bioactive ingredients into familiar dietary patterns without requiring substantial changes in eating habits. Their accessibility, affordability, and compositional flexibility make soups practical food matrices for delivering vegetables, legumes, herbs, mushrooms, and other ingredients of nutritional interest. These characteristics may be particularly relevant for older adults and other populations for whom convenient, palatable, and easy-to-consume foods are important components of a balanced diet. In addition, soups may facilitate the regular consumption of ingredients containing bioactive compounds that have been associated with pathways relevant to cognitive health and healthy ageing.

SOUPS AS FUNCTIONAL FOOD MATRICES

Regular soup consumption is associated with benefits related to nutrition, hydration, and metabolic balance, while soup formulation enables the incorpo-

ration of a wide range of plant-based ingredients, including vegetables, legumes, herbs, and mushrooms. Their semi-liquid structure and high digestibility support nutrient availability and absorption, making soups suitable for diverse population groups, including older adults (Srivastava and Ganjewala 2024). In addition, soups may facilitate the delivery of various bioactive compounds such as polyphenols, carotenoids, dietary fibre, and terpenoids (Fernández-López et al. 2020). Thermal processing applied during soup preparation can also contribute to the retention or enhanced bioaccessibility of selected nutrients, particularly water-soluble vitamins and matrix-bound compounds (Vargha et al. 2024). The concept of soups as functional foods and vehicles for delivering health-related bioactive compounds has been discussed in the literature for over two decades (Andlauer and Fürst 2002). These early considerations highlighted the potential of complex food systems to deliver health-related bioactive compounds while maintaining technological feasibility and sensory acceptance. This perspective provides the basis for current research focused on designing soup formulations as functional food matrices.

Traditional European soups as functional food matrices. Traditional European cuisines provide numerous examples of soups naturally enriched with bioactive compounds derived from wild and cultivated plant species. Ethnobotanical studies conducted in Italy have demonstrated that many wild edible plants used in regional dishes, including soups, are rich sources of polyphenols, flavonoids, vitamins, and minerals (Ranfa et al. 2014; De Falco et al. 2019; Savo et al. 2019). These ingredients contribute to the antioxidant and anti-inflammatory potential of traditional vegetable soups, supporting their classification as naturally functional foods. Importantly, studies have shown that a substantial proportion of phenolic compounds can be retained after thermal processing, indicating that soup preparation does not necessarily diminish their bioactive potential (Savo et al. 2019). In addition to traditional formulations, modern approaches have explored the fortification of soups with specific bioactive compounds, such as carotenoids, further enhancing their functional properties (Pal and Bhattacharjee 2019).

Traditional Asian soups as sources of bioactive ingredients. Traditional Asian cuisines provide numerous examples of soups combining culinary and functional properties through the use of plant-based ingredients rich in bioactive compounds. Ethnobotanical studies from the Kashmir Himalaya region have

described fermented and non-fermented soups prepared from diverse plant materials, including herbs, vegetables, and spices, which contribute organic acids, polyphenols, and flavonoids associated with antioxidant and digestive effects (Singh et al. 2016). These preparations highlight the long-standing use of soups as multifunctional dietary components within local food systems. In South India, traditional soups such as rasam, prepared from mixtures of spices and herbs, represent complex phytochemical systems containing polyphenols, organosulfur compounds, and essential oils with documented biological activity (Mishra et al. 2019). Functional enhancement of such formulations, for example through the addition of spirulina, has been shown to improve nutritional status indicators, including iron-related parameters (Rani and Paulraj 2013).

Across broader Asian food traditions, various plant materials incorporated into soups provide bioactive compounds such as flavonoids, carotenoids, and isoflavones with antioxidant and enzyme-modulating properties (Masih et al. 2019; Malravizshi et al. 2020; Li et al. 2021). These examples illustrate that traditional soup formulations can serve as practical food matrices for incorporating and delivering bioactive compounds within customary dietary patterns. They also highlight the potential of traditional culinary practices to contribute to the intake of diverse phytochemicals and other nutritionally relevant components.

Modern functional soup formulations. Recent studies have focused on the development of standardised soups enriched with bioactive compounds, providing measurable functional properties. Various plant-based ingredients, including pumpkin, goji leaves, chamomile, and mushroom-derived components, have been incorporated into soup formulations to enhance their content of carotenoids, polyphenols, and other phytochemicals (Delgado-Nieblas et al. 2017; Lopatriello et al. 2017). Such formulations have been shown to exhibit increased antioxidant capacity and improved nutritional profiles, reflecting the potential of soups as effective carriers of bioactive compounds (Kalsoom et al. 2021; Pathania et al. 2024). In some cases, fortification strategies have also been associated with enhanced biological activity, including enzyme-modulating and metabolic effects (Hussain et al. 2022), indicating the applicability of these systems in functional food design. Overall, these findings demonstrate a transition from traditional soup preparations to scientifically designed formulations with defined composition and functionality. This approach highlights the role of soups as versatile food matrices enabling

targeted delivery of bioactive compounds through everyday diets.

HEALTH EFFECTS OF SOUP CONSUMPTION

Beyond their nutritional value, soups have been associated with several physiological and clinical outcomes in observational and intervention studies. These include effects related to weight management, metabolic regulation, cardiovascular health, and overall diet quality. Because many of these factors are recognised contributors to healthy brain ageing (as elements of the metabolic syndrome), they are briefly discussed here before addressing evidence more directly related to cognitive health. To facilitate interpretation of the available literature, evidence discussed in this review was categorised into three levels: direct evidence obtained from soup-based interventions, ingredient-based evidence related to foods commonly incorporated into soups, and mechanistic evidence derived from isolated compounds, extracts, cell models, and animal studies (Table 1). This distinction is important because the majority of currently available evidence supporting cognitive health originates from ingredient-based and mechanistic studies, whereas direct soup-specific evidence remains limited.

Importantly, the biological activities discussed throughout this review are primarily associated with individual bioactive compounds and food ingredients commonly incorporated into soups rather than with soup consumption itself. Therefore, soups are considered here principally as food matrices capable of delivering such compounds within habitual dietary patterns.

This section summarises the currently available direct evidence from soup-based interventions.

Weight management and metabolic regulation. Several human studies indicate that regular soup consumption supports healthy body composition and improved metabolic markers. Soups are known to enhance satiety and reduce subsequent energy intake. Controlled feeding studies demonstrated that consum-

ing soup as a preload before a main meal significantly decreases hunger and total calorie intake compared with solid foods of the same composition (Flood and Rolls 2007). In a U.S. population-based cohort, habitual soup consumers showed lower body mass index (BMI), reduced waist circumference, better dietary energy density and improved lipid and glucose profiles compared to non-consumers, even after adjusting for confounders (Zhu and Hollis 2014). A clinical trial involving a vegetable-based soup reported improvements in blood rheology, which may positively affect microcirculation and tissue perfusion (Naghedi-Baghdar et al. 2018). Furthermore, a pilot study conducted among individuals with type II diabetes and hypertension revealed that daily consumption of a functional 'Covi-soup' for three months led to a measurable reduction in systolic and diastolic blood pressure as well as fasting blood glucose levels (Sagam et al. 2023).

These findings collectively suggest that regular inclusion of soups in the diet may contribute to metabolic balance through caloric moderation, enhanced nutrient density, and improved haemodynamic parameters.

Cardiovascular and anti-inflammatory effects. The cardioprotective effects of functional soups are attributed to their high content of antioxidant and anti-inflammatory phytochemicals, as well as their typically low sodium and fat content. In individuals at high cardiovascular risk, regular consumption of gazpacho (cold vegetable soup rich in tomato, olive oil, garlic, and pepper polyphenols) was associated with significantly lower blood pressure and improved endothelial function (Medina-Remón et al. 2013).

Soups containing polyphenol- and carotenoid-rich ingredients (such as carrots, pumpkin, and tomato) may further modulate oxidative stress, enhance nitric oxide bioavailability, and inhibit inflammatory mediators like COX-2 and NF- κ B. By delivering bioactive molecules in a thermally stable and bioavailable form, soups can act as a gentle dietary intervention supporting vascular health and inflammation control (Bondonno et al. 2015; Di Pietro et al. 2020).

Table 1. Levels of evidence discussed in this review

Evidence category	Description	Examples
Direct evidence	studies evaluating soup consumption or soup-based interventions	gazpacho, barley soup, Covi-soup
Ingredient-based evidence	studies on foods commonly incorporated into soups	vegetables, mushrooms, allium species
Mechanistic evidence	studies on isolated compounds, extracts, cell cultures and animal models	quercetin, lutein, curcumin, β -glucans

Cognitive, psychological, and stress-related benefits. Recent studies highlight the role of soups in improving cognitive and psychological well-being. In a workplace intervention, Yajima et al. (2015) found that daily consumption of soup in the afternoon reduced both physical and mental fatigue in employees after two weeks, suggesting benefits for mood and stress resilience. The integration of multiple bioactive compound groups, including polyphenols, carotenoids, terpenoids, dietary fibres, and mushroom metabolites, within a single soup formulation enables synergistic physiological effects supporting cognitive health (Yajima et al. 2015). A clinical study demonstrated that daily intake of a frozen, ready-to-eat barley and pigmented vegetable soup (40% barley, 60% mixed vegetables) for two weeks significantly increased plasma lutein and β -carotene levels and enhanced total antioxidant capacity in healthy adults (Bacchetti et al. 2015). This nutritional diversity is particularly relevant given the multifactorial pathogenesis of neurodegenerative diseases, such as Alzheimer's and Parkinson's, where oxidative stress, chronic low-grade inflammation, and gut–brain axis dysregulation play pivotal roles (Heneka et al. 2015; Ammar et al. 2020; Prakash and Verma 2024). Functional soups enriched with such ingredients may serve as practical food matrices for delivering

compounds associated with pathways relevant to cognitive function; however, direct evidence demonstrating improvements in cognitive performance following soup consumption remains limited.

DELIVERY OF COGNITION-RELATED BIOACTIVE COMPOUNDS THROUGH FUNCTIONAL SOUP MATRICES

Functional soups deliver numerous classes of bioactive compounds that have been associated with pathways relevant to cognitive health. As shown in Table 2, these compounds originate from vegetables, herbs, mushrooms and legumes commonly incorporated into soup formulations. Their potential contribution depends not only on their biological activity but also on the soup matrix, technological processing and bioaccessibility. Because direct evidence from soup-based interventions remains limited, the following sections summarise primarily ingredient-based and mechanistic evidence while discussing these compounds in the context of functional soup formulations. Soups represent one possible form in which these compounds can be consumed. Indeed, this is a very good strategy, as many of these ingredients (e.g. garlic, onion, leek,

Table 2. Main groups of bioactive compounds in functional soups and their relevance to cognitive domains (Johnson 2012; Austin 2017; Feeney et al. 2017; Jabir et al. 2018; Shahidi and Yeo 2018; Cha et al. 2024)

Bioactive compound group	Main sources in soups	Potentially associated cognitive domains	Main mechanisms relevant to cognition
Polyphenols	onion, leek, asparagus, sea buckthorn, herbs, mushrooms	memory, learning, executive functions	antioxidant activity, inhibition of AChE/BChE, modulation of Nrf2 and NF- κ B pathways
Carotenoids	carrot, pumpkin, tomato, spinach, sweet potato	attention, processing speed, memory	protection of neuronal membranes, reduction of oxidative stress, support of synaptic signalling
Terpenoids	rosemary, sage, oregano, thyme, spices	attention, working memory, executive functions	anti-inflammatory effects, modulation of neurotransmission, inhibition of COX-2 and iNOS
Dietary fibres (prebiotics)	leek, onion, garlic, asparagus, Jerusalem artichoke, barley	executive functions, memory (indirect)	gut–brain axis modulation, SCFA production, reduction of neuroinflammation
Mushroom-derived bioactives	shiitake, oyster, button mushrooms, lion's mane	memory, learning, executive functions	ergothioneine antioxidant activity, β -glucan immunomodulation, stimulation of NGF and BDNF
Allium organosulfur compounds	garlic, onion, leek	memory, attention	antioxidant and anti-inflammatory effects, cholinesterase inhibition, vascular support
Micronutrients (minerals and vitamins)	vegetable- and legume-based soups, fortified soups	global cognitive performance	support of antioxidant enzymes, neurotransmitter synthesis, vascular and metabolic regulation

BDNF – brain-derived neurotrophic factor; NGF – nerve growth factor; SCFA – short-chain fatty acids; AChE – acetylcholinesterase; BChE – butyrylcholinesterase

or selected mushrooms) have a taste and/or aroma that may be unacceptable to some consumers. In this way, the taste and aroma of these raw materials can be easily masked in the soup. Furthermore, selected soup components have an unsuitable texture when raw (e.g. leek and most mushrooms), so they require a change in consistency. The simplest method, feasible in any household, is heating/overcooking at atmospheric pressure and then puréeing to achieve a consistency similar to a fruit smoothie, which significantly increases the potential bioavailability of the bioactive ingredients.

Evidence regarding the bioactive compounds discussed in this section is derived primarily from ingredient-based and mechanistic studies, whereas direct evidence from soup-based interventions remains limited. Functional soups serve as complex food matrices capable of delivering multiple bioactive compounds whose stability, bioaccessibility and potential biological activity are influenced by ingredient composition and technological processing.

Polyphenol-rich vegetables and herbs, including onion, leek, asparagus, parsley, mushrooms and sea buckthorn, are frequently incorporated into functional soups, making them important dietary matrices for polyphenol delivery. Appropriate thermal processing ($\leq 90^\circ\text{C}$ for 15–20 min) helps preserve a substantial proportion of these compounds while improving the extractability of matrix-bound polyphenols (Călinoiu and Vodnar 2019). Polyphenols have been associated with antioxidant activity, modulation of redox-sensitive pathways (Nrf2 and NF- κ B), reduction of acetylcholinesterase (AChE) and butyrylcholinesterase (BChE) activities, and regulation of gut–brain axis signalling (Jabir et al. 2018; Shahidi and Yeo 2018). However, these effects have been demonstrated predominantly in studies using purified compounds or extracts at concentrations exceeding those achievable through normal soup consumption. Therefore, direct extrapolation of mechanistic findings to functional soups should be interpreted with caution. Similarly, soups prepared from carrot, pumpkin, tomato, spinach or sweet potato provide practical food matrices for carotenoid delivery. Thermal processing disrupts plant cell walls and increases carotenoid extractability, whereas the presence of small amounts of dietary fat or emulsifiers in creamy soups further enhances their bioaccessibility (Yuan et al. 2020; Molteni et al. 2022). Carotenoids, particularly β -carotene, lutein, zeaxanthin and lycopene, have been associated with protection against oxidative stress, maintenance of neuronal membranes and cognitive function (Johnson 2012; Feeney et al. 2017).

Nevertheless, current evidence originates largely from studies evaluating overall dietary carotenoid intake rather than soup-specific interventions.

Herbs commonly incorporated into soups, including rosemary, sage, oregano and thyme, enrich soup matrices with terpenoids that generally remain stable under typical culinary processing. These compounds have demonstrated antioxidant, anti-inflammatory and neuroprotective activities through modulation of COX-2, iNOS and neurotransmission pathways, while selected compounds such as rosmarinic acid, carnolic acid and 1,8-cineole have shown beneficial effects on memory and attention in experimental and preliminary clinical studies (Moss and Oliver 2012; Habtemariam 2023; Mirza et al. 2023). However, available evidence is based predominantly on isolated compounds and animal models rather than functional soup formulations.

Functional soups also represent convenient matrices for delivering prebiotic dietary fibres naturally present in leek, onion, garlic, asparagus and Jerusalem artichoke. Because these ingredients are consumed within a hydrated, semi-liquid matrix, soups may facilitate regular fibre intake, particularly among older adults. Prebiotic fibres contribute to gut microbiota modulation and short-chain fatty acid production, processes implicated in gut–brain communication and neuroinflammation (Austin 2017; Hughes et al. 2022). In addition, the viscosity and slow gastric emptying of fibre-rich soups may improve glycaemic regulation (Mihai et al. 2018). Nevertheless, the reported cognitive benefits are attributed primarily to long-term dietary fibre intake rather than soup consumption itself (La Torre et al. 2021).

Mushrooms incorporated into functional soups provide ergothioneine, β -glucans, hericenones, erinacines and other bioactive compounds within a highly acceptable food matrix. Thermal processing generally preserves these compounds sufficiently to allow dietary delivery, although bioavailability depends on formulation and processing conditions. Mushroom-derived bioactives exhibit antioxidant, immunomodulatory and neurotrophic activities, including stimulation of nerve growth factor (NGF) and brain-derived neurotrophic factor (BDNF) synthesis (Fu and Shen 2022; Cha et al. 2024). Epidemiological studies further associate regular mushroom consumption with a lower risk of mild cognitive impairment and improved cognitive performance (Hu et al. 2022; Yan et al. 2023). However, these observations relate primarily to mushroom intake rather than mushroom-containing soups.

Species such as *Allium cepa*, *Allium sativum*, and *Allium ampeloprasum* are among the most common functional ingredients in soups. They are rich in organosulfur compounds (allicin, S-allyl cysteine), flavonoids (quercetin, kaempferol), and fructooligosaccharides with prebiotic properties. These bioactives demonstrate antioxidant, anti-inflammatory, and cholinesterase-inhibitory activity, supporting cognitive performance and vascular health (Block 2010; El-Saber Batiha et al. 2020; Chakraborty et al. 2022). Herbs and spices supply compounds such as rosmarinic acid, carnolic acid and curcumin, while their culinary use facilitates incorporation into soup formulations without substantially compromising sensory acceptance (Moss and Oliver 2012; Habtemariam 2023). Likewise, root vegetables constitute important sources of carotenoids, and controlled thermal processing enhances their release and bioaccessibility within soup matrices (Van Loo-Bouwman et al. 2014; Yuan et al. 2020).

EFFECT OF SOUP PREPARATION METHODS ON STABILITY OF BIOACTIVE COMPOUNDS

Soup preparation methods critically influence the retention and bioaccessibility of bioactive compounds. The stability of these compounds depends primarily on processing intensity, food matrix characteristics, and environmental factors such as pH, oxygen exposure, and lipid content. Table 3 summarises the major preparation and processing approaches applied to soups and their general effects on the stability and bioavailability of key bioactive compounds, which are discussed in detail in the subsections below.

Pasteurisation and sterilisation are commonly used to ensure microbiological safety and are highly effective

for inactivating pathogenic and spoilage microorganisms, yet they inevitably affect thermolabile nutrients and bioactive molecules. For example, a recent study examining vegetable–lentil soup showed reductions of up to 72% for total phenols, 92% for lycopene, and nearly 100% for vitamin C across cooking methods, although overall antioxidant activity increased by up to 46% after thermal treatment (Vargha et al. 2024). This reflects that, while antioxidant activity may persist or even intensify post-cooking, the actual bioaccessible levels of specific compounds can be substantially reduced. Pasteurisation temperatures typically range between 70 °C and 95 °C for 10–30 min, while sterilisation involves heating at 110–130 °C under pressure to achieve commercial sterility (Tewari and Juneja 2007). These treatments induce mild to moderate degradation of heat-sensitive constituents such as water-soluble vitamins (vitamin C, thiamine, folate) and lipophilic antioxidants (vitamin E, carotenoids), depending on exposure time, matrix composition, and pH conditions (Narra et al. 2024a). For instance, in vegetable-based soups, vitamin C losses during pasteurisation may range from ~20% to 45%, whereas sterilisation (or more intense heat treatments) can cause reductions up to ~65–70% (Mieszczakowska-Frąc et al. 2021). Similarly, thiamine and folate losses of 10–30% have been reported in thermally processed mixed-vegetable purées and ready-to-eat soups. Despite these losses, moderate pasteurisation can improve bioaccessibility of certain compounds. The partial breakdown of plant cell walls and release of bound phenolics or carotenoids increases extractability and absorption during digestion (Holland et al. 2020). Therefore, while pasteurisation causes measurable nutrient reductions, it can simultaneously enhance the bioavailability of fat-soluble and matrix-bound bioactives, an effect particularly

Table 3. Effect of soup preparation and processing methods on stability and bioaccessibility of bioactive compounds

Processing method	Typical conditions	Main affected bioactive compounds	General effect on stability/bioaccessibility
Boiling/ conventional cooking	90–100 °C, short–moderate time	polyphenols, vitamin C, carotenoids	partial losses of heat-sensitive compounds; increased bioaccessibility of carotenoids
Pasteurisation	70–95 °C, 10–30 min	polyphenols, vitamins, carotenoids	moderate degradation; improved extractability of matrix-bound compounds
Prolonged thermal treatment / sterilisation	≥ 110 °C, extended time	vitamins, carotenoids, phenolics	significant degradation of thermolabile compounds; reduced sensory quality
High hydrostatic pressure (HHP)	400–600 MPa	polyphenols, vitamins	high retention of bioactives; minimal thermal degradation
Pulsed electric field (PEF)	high-voltage pulses, non-thermal	Vitamin C, phenolics, carotenoids	very high retention; enhanced extraction and bioaccessibility
Matrix-related factors	pH, particle size, lipid content	multiple compound classes	modulation of stability, release, and absorption during digestion

relevant in complex food matrices such as soups. Sterilisation (typically 121 °C for 15–20 min) provides long shelf-life but induces greater degradation of labile phytochemicals and sensory quality deterioration (darkening, flavour loss) due to Maillard and oxidation reactions (Vargha et al. 2024). For the above reasons, functional soup formulations increasingly favour mild pasteurisation combined with high hydrostatic pressure (HHP) or pulsed electric field (PEF) processing to achieve microbial safety while preserving bioactive integrity (Mieszczakowska-Frąc et al. 2021). Innovative non-thermal preservation techniques such as PEF processing and HHP offer compelling advantages. PEF processing accomplishes microbial inactivation through short highvoltage pulses that create micropores in microbial membranes without prolonged heating. Studies have demonstrated that PEF-treated cold vegetable soups (e.g. gazpacho) retain significantly more vitamin C, between 84% and 97%, compared to analogous soups pasteurised at 90 °C, which retain only around 79% (Rodríguez-Roque et al. 2015; Mieszczakowska-Frąc et al. 2021). Further, PEF has minimal impact on phenolic, carotenoid, and vitamin A compounds in treated foods, preserving both the integrity and bioavailability of these nutraceutical components (Vargha et al. 2024). Evidence also suggests that PEF may actually enhance extraction of certain bioactives from plant matter. For example, PEF pretreatment improved yields of phenolics and antioxidant activity by approximately 20–22% compared to conventional extraction methods in plant-based systems (Nowosad et al. 2021). Ohmic heating is a mild thermal technique where electrical current directly heats food and can also reduce cooking time and microbial load while preserving sensory and nutritional quality better than conventional boiling, though specific data on soups remain limited (Sain et al. 2024). The extent of nutrient degradation is influenced by food acidity. Lower pH environments may enhance the thermal stability of carotenoids and phenolic compounds, while acidic conditions generally improve the stability of ascorbic acid by limiting oxidative degradation (Patras et al. 2010; Narra et al. 2024b). Acidic conditions (pH < 5) often stabilise ascorbic acid and some phenolic acids by inhibiting oxidation reactions, whereas neutral or alkaline conditions tend to accelerate their degradation. The presence of natural organic acids (from tomato, sea-buckthorn, or citrus ingredients) can therefore protect redox-sensitive molecules. Conversely, traces of transition metals (Fe, Cu, Mn) naturally present in vegetables or water may catalyse

oxidation and should be chelated by agents such as citric or malic acid. Matrix viscosity and particle size of raw materials significantly influence heat and mass-transfer phenomena, particularly oxygen diffusion and thermal penetration, during soup preparation. In finely puréed soups, reduced particle size and lower structural integrity increase the exposed surface area and decrease internal diffusion distances. This facilitates the release and extraction of intracellular bioactive compounds, including polyphenols and carotenoids, through enhanced disruption of plant tissues and cell walls. However, increased exposure also promotes contact of released compounds with dissolved oxygen and elevated temperatures during processing, which may accelerate oxidative degradation or thermal breakdown of sensitive constituents such as vitamin C and carotenoids (Palermo et al. 2014). Conversely, soups with a coarser particle structure retain larger intact tissue fragments that may partially protect intracellular compounds from oxygen and heat exposure. Intact cell walls can act as physical barriers, reducing diffusion of oxygen and thermal penetration and thereby improving the stability of labile bioactive compounds (Arfaoui 2021). This protective effect, however, is associated with a trade-off, as limited tissue disruption may reduce the release of bioactive compounds into the food matrix and subsequently decrease their theoretical bioaccessibility during digestion. Therefore, particle size represents an important factor influencing the balance between bioactive compound preservation and their potential availability for absorption. Polyphenols, carotenoids, dietary fibre, and various micronutrients often coexist in functional soups. Their interactions can significantly influence their stability and efficacy during digestion. For example, polyphenols have been shown to interact with dietary fibre through hydrogen bonding or hydrophobic associations, which can delay their release and modulate their absorption in the gastrointestinal tract (Cardona et al. 2013). This may be beneficial, as a slow and prolonged release of polyphenols can support long-term antioxidant protection and enhance microbial fermentation in the colon, promoting the production of neuroprotective short-chain fatty acids (Hong et al. 2022). Similarly, carotenoids such as β -carotene or lutein, naturally present in carrots, pumpkin, and sea buckthorn, can interact with dietary fats and polyphenols. While moderate amounts of fat enhance carotenoid absorption, certain polyphenols may inhibit carotenoid micellization, reducing their bioavailability (Reboul 2013). Protein–polyphenol interactions also play a ma-

major role. When soups contain legumes or mushrooms as protein sources, polyphenols may bind to amino acid residues, reducing their free radical scavenging capacity but sometimes increasing resistance to degradation during cooking or digestion (Ozdal et al. 2013). These complexes can act as controlled-release systems for polyphenols, enhancing bioactivity in the lower intestine. However, excessive binding can limit both protein digestibility and polyphenol bioefficacy. On the other hand, some interactions are clearly synergistic. For example, polyphenols and vitamin C (e.g. from parsley or sea buckthorn) can regenerate each other's antioxidant potential and stabilise radical species in aqueous solutions (Lotito and Frei 2006). In mushroom-based soups, ergothioneine has been shown to work synergistically with selenium and polyphenols to enhance cellular antioxidant defence mechanisms (Cheah and Halliwell 2012). Synergistic effects have also been described between polyphenols and carotenoids, where phenolic compounds prevent oxidative degradation of β -carotene and lycopene by scavenging peroxy radicals, thus stabilising carotenoids within emulsified or semi-liquid food systems such as soups (Stahl and Sies 2005; Kaulmann and Bohn 2014). The presence of small amounts of lipids, such as vegetable oils used in cream soups, further promotes the incorporation of lipophilic carotenoids and tocopherols into mixed micelles, enhancing absorption and overall antioxidant efficiency (Reboul 2013). Similarly, polyphenols and certain amino acids, such as cysteine and tryptophan, can interact non-covalently to regenerate reduced antioxidant forms and maintain redox balance in aqueous matrices (Li et al. 2025). Minerals such as zinc, copper, and manganese act as essential cofactors for endogenous antioxidant enzymes (e.g. superoxide dismutase and glutathione peroxidase), and their presence in vegetable or legume-based soups enhances the overall redox buffering capacity when combined with dietary phenolics and carotenoids (Niki 2010). Dietary fibre components, particularly β -glucans and inulin-type fructans, can also exert synergistic effects by protecting phenolic compounds from early oxidation during cooking and digestion (Jakobek et al. 2022), thereby prolonging their antioxidant action and promoting colonic fermentation into neuroprotective short-chain fatty acids (Tarko et al. 2020). Finally, selected terpenoids (e.g. carnosic acid) or polyphenols (e.g. rosmarinic acid) may potentiate the radical-scavenging and anti-inflammatory activities of flavonoids, producing additive or synergistic inhibition of pro-oxidant enzymes like COX-2 and iNOS (Habtemariam

2023). Moreover, fermentation or enzymatic digestion in the gastrointestinal tract can release bound forms of polyphenols or peptides, enabling them to interact later in the colon with microbial enzymes or cellular targets (Wang et al. 2022; Subbiah et al. 2024; Nemzer et al. 2025). In this way, initial matrix interactions in soup formulations can have delayed but potent biological effects.

Processing-related implications for cognitive health. The preservation of bioactive compounds during soup processing may be relevant to the delivery of ingredients associated with pathways involved in cognitive health. For example, improved retention and bioaccessibility of polyphenols may increase the availability of compounds reported to modulate oxidative stress, inflammatory responses and cholinergic signalling (Jabir et al. 2018; Shahidi and Yeo 2018). Similarly, enhanced bioaccessibility of carotenoids following thermal processing may improve the delivery of compounds associated with neuronal protection and redox regulation (Johnson 2012; Feeney et al. 2017; Yuan et al. 2020). Preservation of dietary fibres, β -glucans and other prebiotic components may also support gut microbiota composition and gut–brain axis interactions (Austin 2017; La Torre et al. 2021). However, the relationship between bioaccessibility and biological efficacy should be interpreted with caution. Increased retention or release of bioactive compounds during digestion does not necessarily translate into improved bioavailability, physiological activity, or measurable cognitive outcomes in humans. Furthermore, the majority of available evidence linking these compounds to cognitive health originates from ingredient-based and mechanistic studies rather than soup-specific interventions. Therefore, while processing technologies such as HHP and PEF may enhance the preservation and delivery of bioactive compounds, their direct impact on cognitive function remains to be established through well-controlled human studies.

SAFETY CONSIDERATIONS FOR SOUP MATRICES

Functional soups prepared from commonly consumed food ingredients and subjected to standard culinary or industrial processing are generally considered safe for consumption. As food matrices, soups are typically produced under high-moisture conditions and moderate temperatures, resulting in concentrations of potentially harmful compounds that are well below levels associated with adverse effects. Nevertheless,

safety should be considered during the development of functional soup formulations, particularly when concentrated bioactive ingredients, herbal extracts, or unconventional raw materials are incorporated. Most naturally occurring anti-nutritional factors present in vegetables and legumes, including lectins, saponins, alkaloids and oxalates, are substantially reduced during cooking. However, improperly prepared legumes may retain biologically active lectins such as phytohaemagglutinin (Mishra et al. 2019). Likewise, only verified edible mushroom species should be used in functional soup formulations because wild mushrooms may contain potent neurotoxins (Govorushko et al. 2019). Thermal processing may also generate selected Maillard reaction products, particularly when ingredients are roasted or sautéed before incorporation into soups. However, because soups are generally cooked under high-moisture conditions at temperatures close to 100 °C, the formation of these compounds is considerably lower than in baked or fried foods and is unlikely to represent a major safety concern under typical preparation conditions (Lund and Ray 2017). The use of concentrated extracts or highly enriched formulations requires additional attention. High doses of isolated flavonoids may exhibit pro-oxidant effects in experimental models (Galati and O'Brien 2004; Tang and Zhang 2022), while certain herbal extracts and essential oils may interact with drug-metabolising enzymes or increase the risk of hypersensitivity when consumed in concentrated forms (Mohamed et al. 2022). Similarly, common soup ingredients such as celery, soy, gluten-containing cereals and dairy products remain relevant food allergens and require appropriate labelling in accordance with EU Regulation 1169/2011.

Overall, the concentrations of potentially harmful compounds in conventional soup servings are generally far below toxicological thresholds (Manach et al. 2004; Spencer et al. 2008; EFSA Panel on Food Contact Materials, Enzymes, Flavourings and Processing Aids 2011; Abdelshafy et al. 2022; Watier-Grillot et al. 2023). Therefore, functional soups prepared from conventional food ingredients can be regarded as safe food matrices, whereas formulations containing concentrated extracts or novel ingredients may require additional toxicological evaluation before long-term dietary use.

LIMITATIONS OF CURRENT EVIDENCE

Despite the growing interest in functional foods supporting cognitive health, several important limitations should be considered when interpreting

the available evidence. First, direct evidence linking soup consumption with cognitive outcomes remains limited. It should be emphasised that, for the purposes of this review, all studies identified in the databases that directly addressed the impact of soup consumption on cognitive outcomes and diseases associated with metabolic syndrome were discussed. Most studies evaluating soups have focused on nutritional status, metabolic parameters, cardiovascular markers, or general well-being rather than specific cognitive endpoints (Bacchetti et al. 2015; Yajima et al. 2015; Sagam et al. 2023). Consequently, the evidence directly supporting cognitive benefits of soup consumption is still scarce. On the other hand, evidence regarding the ingredients used in soups indirectly suggests that soup consumption could potentially contribute to the prevention of these diseases. Therefore, a substantial proportion of the literature discussed in this review is based on ingredient-level evidence, as numerous studies have reported beneficial effects of polyphenols, carotenoids, dietary fibres, mushroom-derived compounds and terpenoids on pathways associated with cognitive health, including oxidative stress, inflammation, cholinergic neurotransmission, and gut–brain axis interactions (Shahidi and Yeo 2018; Ammar et al. 2020; Habtemariam 2023). However, these findings cannot be directly extrapolated to soup-based formulations, as the concentrations, bioaccessibility, and interactions of bioactive compounds may differ considerably within complex food matrices. Furthermore, much of the mechanistic evidence originates from *in vitro* studies, animal models, or investigations using purified compounds and concentrated extracts (Jabir et al. 2018; Cha et al. 2024; Qiu et al. 2024). The doses applied in such studies often exceed levels achievable through normal dietary consumption of soups, which may limit their direct relevance to human nutrition. Another challenge is the substantial variability among soup formulations. Differences in ingredient composition, processing conditions, serving size, and storage practices may significantly influence the stability, bioaccessibility, and biological activity of bioactive compounds (Călinoiu and Vodnar 2019; Holland et al. 2020; Vargha et al. 2024). This heterogeneity complicates comparisons between studies and limits the possibility of drawing generalised conclusions.

An additional limitation concerns the concentrations of bioactive compounds achievable through normal soup consumption. While many studies report beneficial effects of isolated polyphenols, carotenoids,

terpenoids, mushroom-derived compounds, or other phytochemicals, these investigations frequently employ purified compounds, concentrated extracts, or doses substantially exceeding those obtainable from a typical serving of soup. A standard soup portion (approximately 250–400 mL) consists largely of water, and the concentrations of individual bioactive compounds are generally lower than those used in experimental or clinical supplementation studies. Therefore, potential benefits associated with soup consumption are more likely to reflect the cumulative effects of regular dietary exposure to diverse bioactive compounds and overall dietary quality rather than the specific pharmacological effects of individual compounds delivered at therapeutic doses.

Therefore, while current evidence supports the biological plausibility of functional soups as vehicles for delivering cognition-related bioactive compounds, well-designed human intervention studies evaluating standardised soup formulations and clinically relevant cognitive outcomes are still needed.

CONCLUSION

Soups represent versatile and culturally accepted food matrices that facilitate the incorporation and dietary delivery of a wide range of bioactive compounds. Their compositional flexibility, consumer acceptance, and compatibility with diverse dietary patterns make them promising vehicles for functional ingredients associated with biological pathways relevant to healthy brain ageing and cognitive health.

However, current evidence supporting the cognitive benefits of soups remains limited. Most available data originate from studies of individual ingredients, isolated bioactive compounds, or experimental models rather than direct evaluations of soup consumption. Consequently, functional soups should be regarded primarily as food matrices enabling the delivery of bioactive compounds rather than as independently proven neuroprotective interventions.

Future research should focus on standardised soup formulations, the effects of technological processing on bioactive compound stability and bioaccessibility, and well-designed human intervention studies to determine whether soup-based formulations provide measurable health benefits. Such studies should include a sufficiently long intervention period and account for participants' overall dietary intake, which may influence the observed effects of soup consumption, as well as differences in health status, genetic pre-

disposition, stimulant consumption, physical activity and other relevant factors.

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