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SUSTAINABLE USE OF SEA BUCKTHORN BY-PRODUCT AS FUNCTIONAL INGREDIENT IN FOOD APPLICATIONS: TRENDS AND CHALLENGES

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Abstract

Sea buckthorn juice processing generates substantial quantities of pomace, primarily consisting of seeds and peels, often discarded despite its potential as a valuable food ingredient. This work provides an overview of the literature on the conditioning, characterization, and valorization of sea buckthorn pomace (SBP) as a functional food ingredient. SBP is rich in valuable bioactive compounds and nutrients, allowing its transformation into a low-cost, highly functional food ingredient supporting circular economy principles and current food industry trends focused on sustainability and resource efficiency. Valorization of SBP for the development of value-added food products has attracted scientific interest due to its complex chemical composition, with high levels of phenolic compounds, flavonoids, proteins, and dietary fibers, enhancing both the nutritional and functional properties. This review addresses challenges related to SBP drying to preserve bioactive compounds and discusses applications in bakery, pastry, chocolate, dairy, and meat products, as well as its use as a natural antioxidant to improve the oxidative stability of edible oils. Overall, sustainable SBP exploitation provides environmental, economic, and nutritional benefits, supporting the development of foods with an enhanced functional profile.

Key words: *nutritional and functional benefits, sustainable use, upcycling of sea buckthorn pomace, value-added foods.*

INTRODUCTION

Sea buckthorn (*Hippophae rhamnoides* L.) is a small tree species belonging to the *Elaeagnaceae* family, recognized for its high tolerance to drought, strong winds, sandy environments, and saline soils (Tie et al., 2024). It is widely known under several common names, including vinegar tree, yellow thorn, sour willow, and black thorn (Teng et al., 2024). The classification of genus *Hippophae* has been modified over the years. Some studies found that originally, it was strong by only one species, namely *H. rhamnoides*, with 3 subspecies, namely *rhamnoides, salicifolia*, and *tibetana. Then,* the species was divided into nine subspecies: *carpatica, caucasica, fluviatilis, gyantsensis, mongolica, rhamnoides, sinensis, turkestanica, and yunnanensis* (Swenson et al., 2008).

Sea buckthorn (SB) is a highly resilient plant species, characterized by strong tolerance to drought, cold, salinity, and alkaline soils. Owing to its remarkable adaptability, it can survive in extreme environmental conditions, including temperatures as low as −40°C, as shown in Figure 1 (Chen et al., 2023).

In its natural distribution range, sea buckthorn occurs in North-Western Europe, Central Asia, China, Mongolia, the Caucasus, and Siberia (Zhu et al., 2025). In contrast, in North America, it has been cultivated experimentally for more than 20 years. Although efforts have been made to introduce it into commercial agriculture in the United States and Canada, it is still considered an exotic species in these regions. Its broader commercialization is limited by gaps in knowledge related to cultivation practices, the phytochemical

composition of the fruit, and potential market development (Danielski & Shahidi, 2025).

In the 1980s, sea buckthorn was included in the first group of medicinal and edible plant species recognized by the former Ministry of Health of China (Chen et al., 2023). Sea buckthorn (SB) berries are highly valued for their nutritional content and health-promoting properties, which have long been acknowledged in traditional medicine, including anti-inflammatory and detoxifying effects, as well as benefits for the regeneration and health of skin and hair. These properties are attributed to the presence of more than 200 nutritional and bioactive compounds. The wide environmental diversity across growing regions also contributes to variations in fruit quality and biochemical composition. As a result, sea buckthorn is already incorporated into a variety of food products.

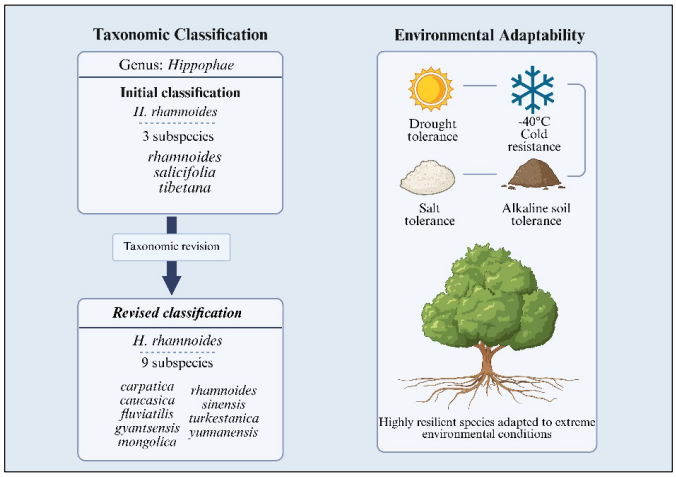

Figure 1. Taxonomic evolution and environmental adaptability of *Hippophae rhamnoides* L. (created in BioRender, https://BioRender.com, accessed in 25.03.2026)

The most common products derived from sea buckthorn include juices, jams, wines, pies, and liqueurs. Research has focused on identifying the compounds responsible for the fruit's characteristic and sometimes unpleasant taste. Among the organic acids present in sea buckthorn berries, malic and quinic acids are the predominant components and are largely associated with their pungent flavor (Jaśniewska & Diowksz, 2021).

The findings reported by Yang et al. (2011) and Jaśniewska & Diowksz (2021) indicate that the health-promoting effects of sea buckthorn (SB) have been acknowledged, mainly due to its high concentration of bioactive constituents such as antioxidants, phytosterols, essential fatty acids, amino acids, and vitamins C, K, and E. Moreover, the fruit is characterized by a relatively low sugar content and a complex profile of volatile compounds that shape its distinctive aroma. This particular sensory profile, together with its nutritional value and documented health benefits, supports the use of sea buckthorn as a valuable raw material in various cosmetic, pharmaceutical, and food applications (Jaśniewska & Diowksz, 2021).

A study conducted by Liu et al. (2021) classified sea buckthorn, alongside other fruits, as a "superfruit" due to its rich content of bioactive phytochemicals and associated health-promoting effects, particularly its high levels of antioxidant compounds. "Superfruit" is a term used to describe fruits that are believed to provide health benefits or therapeutic value, based on certain aspects of their nutritional composition or their overall nutrient density. Sea buckthorn contains a wide range of chemical constituents, including vitamins, carotenoids, and flavonoids (Wang et al., 2022). According to the same study, the juice exhibited elevated concentrations of vitamin E, vitamin C, and flavonoids, quantified at 13.3, 1.540, and 1.182 mg/L, respectively. More than 75% of the total

vitamin E content occurs as α-tocopherol, whereas isorhamnetin is recognized as one of the most biologically active flavonol aglycones present in sea buckthorn juice (Liu et al., 2021).

The global food processing industry produces large volumes of by-products, and their management is increasingly critical due to population growth and resource constraints (Metzner Ungureanu et al., 2020; Caponio et al., 2022; Chang et al., 2022). Fruit processing residues are rich in bioactive compounds with antioxidant activity, which may benefit human health. Valuable biological constituents can be recovered from plant-derived waste streams and converted into food ingredients, dietary supplements, or functional products (Wu et al., 2024).

Within this framework, recent research has increasingly focused on sea buckthorn by-products, recognizing their potential as valuable sources for supplements and functional ingredients. By incorporating sea buckthorn by-products as whole powders, functional fractions, or sources of extracted bioactive compounds, the food industry can enhance product quality and nutritional value while promoting waste valorization and reducing environmental impact. A continuous challenge in this field is the identification of processing methods that ensure minimal environmental impact and reduced risks to consumer health, while also lowering energy consumption and employing safe solvents (Stanciu & Popa, 2022).

Due to its delicate epicarp and high moisture content (80-90%), sea buckthorn fruit has limited post-harvest stability and is highly susceptible to microbial contamination, leading to rapid degradation and spoilage (Geng et al., 2023). Consequently, processing activities within the sea buckthorn industry are mainly directed toward beverage production and oil extraction. However, sea buckthorn pomace (SBP), the solid residue remaining after juice extraction, is frequently discarded, resulting in considerable resource losses (Zhou et al., 2024). Given its valuable nutritional and health-promoting properties, SBP represents a promising ingredient for the development of novel food products.

The recovery of processing by-products is closely aligned with the principles of the circular economy, aiming to reduce the environmental impact of production processes while increasing their economic value (Caponio et al., 2022). This perspective supports the expanded valorization of food industry residues by recovering and applying biologically active compounds across various sectors of the food industry (Luntraru et al., 2022).

The initial stage of by-product utilization involves conditioning immediately after processing to ensure biochemical and microbiological stabilization, particularly due to the high moisture content of most residues, followed by further transformation or extraction steps prior to final application in food products (Zhou et al., 2024).

Thermal treatments and drying methods applied to raw by-products may significantly influence quality attributes, particularly during dehydration processes. Drying can be performed using conventional techniques or advanced methods such as freeze-drying (lyophilization), infrared drying, and pulsed vacuum drying (Metzner Ungureanu et al., 2020; Jaśniewska & Diowksz, 2021; Zhou et al., 2024).

The main by-product generated during sea buckthorn juice processing is fruit pomace, consisting of seeds, peel, fibre, and residual pulp. Its high moisture content, approximately 67% (Zhou et al., 2024), contributes to its limited stability and susceptibility to microbial and biochemical degradation. Fruit peels are important sources of cellulose, hemicellulose, nutrients, and phenolic compounds (Kitrytė et al., 2017; Chang et al., 2022), while seeds represent valuable sources of proteins and lipids. Overall, fruit pomace contains approximately 50% fibre along with various bioactive compounds, highlighting its potential as a functional ingredient (Pedro et al., 2024).

The recovery of bioactive compounds from sea buckthorn pomace represents a critical stage, depending on the chosen extraction method and operational conditions, as these factors significantly affect extraction efficiency and compound stability. The study conducted by Luntraru et al. (2022) addresses the valorization of sea buckthorn juice by-products

through the extraction of bioactive compounds using two methods: maceration and ultrasound-assisted extraction (UAE). The findings indicate that UAE markedly increases the total polyphenol content, flavonoid concentration, and antioxidant activity compared to conventional maceration, highlighting the importance of optimizing extraction techniques from a technological perspective (Luntraru et al., 2022). From a broader perspective, Caponio et al. (2022) present a comprehensive view on the valorization of food industry by-products within the circular economy framework. Rather than focusing on a single raw material, it discusses multiple agro-industrial residues (including sea buckthorn flour, grape pomace, olive mill wastewater, and others) and emphasizes sustainable strategies, green extraction technologies, and functional food applications. While Luntraru et al. (2022) provide detailed analytical data on the composition and antioxidant activity of sea buckthorn pomace extracts, Caponio et al. (2022) extend the discussion to a broader sustainability framework. Consequently, Luntraru et al. (2022) contribute to the understanding of extraction efficiency and bioactive compound recovery, whereas Caponio et al. (2022) emphasize the environmental and economic significance of by-product valorization in the food sector.

Figure 2 provides a circular economy model in sea buckthorn processing, illustrating the transformation of berries into value-added products through by-product valorisation.

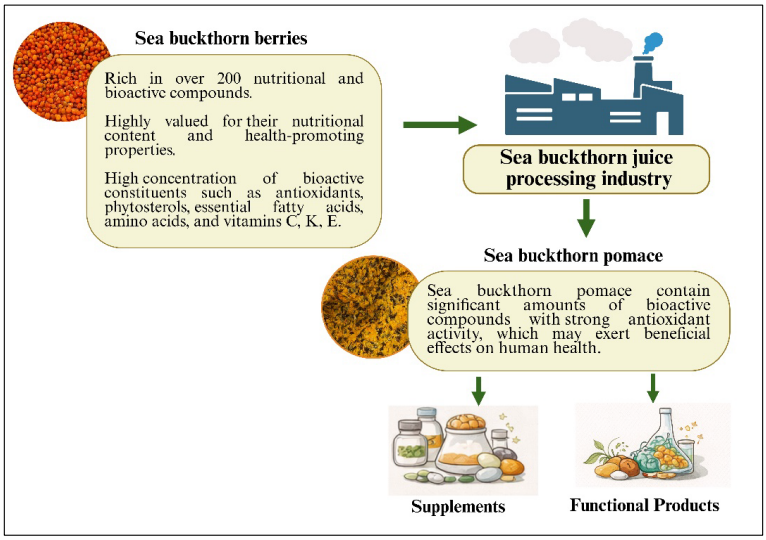

Figure 2. Circular economy model in sea buckthorn processing and by-product valorisation (created in BioRender, https://BioRender.com, accessed in 25.03.2026).

MATERIALS AND METHODS

This study was designed as a systematic literature review aimed at identifying and analyzing innovative strategies for the valorization of sea buckthorn (*Hippophae rhamnoides* L.) pomace and its applications in food systems.

The literature search was conducted using several major scientific databases, including Google Scholar, MDPI, ScienceDirect, SpringerLink, PubMed, Scopus, and Web of Science. The search strategy was based on combinations of relevant keywords such as "sea buckthorn pomace", "sea buckthorn by-products", "phytochemical composition", "functional foods", "food applications", "bioactive compounds", and "food enrichment".

Inclusion criteria comprised peer-reviewed articles published in English, focusing on the nutritional, phytochemical, and functional properties of sea buckthorn pomace, as well as its applications in food products. Review

papers and experimental studies were both considered, provided they contributed relevant data to the topic. Exclusion criteria included articles lacking full-text access, studies not directly related to sea buckthorn pomace, and publications outside the scope of food applications.

The selection process involved an initial screening of titles and abstracts, followed by full-text evaluation of potentially relevant studies, with priority given to recent publications. The collected literature was systematically analyzed and grouped into two main thematic sections: (1) nutritional and phytochemical properties of sea buckthorn pomace, and (2) sea buckthorn pomace as a functional food ingredient. The second category was further structured based on specific food applications, including: incorporation into jelly and candy formulations, chocolate products, beverages, bakery and pastry products, and edible oils for bioactive enrichment.

The methodology relied on critical analysis, comparison, and synthesis of the selected studies, allowing the identification of current research trends, technological approaches, and existing gaps in the valorization of sea buckthorn pomace.

RESULTS AND DISCUSSIONS

1. Nutritional and phytochemical properties of sea buckthorn pomace

Sea buckthorn pomace (SBP), consisting of seeds and residual solid fractions remaining after juice extraction, is subjected to drying, resulting in a nutritionally valuable by-product characterized by a high dry matter content of approximately 93-94%, confirming its low residual moisture and suitability for storage and further utilization (Nour et al., 2021).

Lipid content has been reported at approximately 12% (dry matter) (Kaminskytė et al., 2025) and up to approximately 20% (dry matter) (Peng et al., 2024). The lipid component is largely associated with residual seed material, as previously reported (Dienaitė et al., 2020; Sharma et al., 2022; Xiao et al., 2024). The fatty acid profile is nutritionally favourable, with monounsaturated fatty acids representing approximately 53% of total fatty acids and an n-6/n-3 ratio of approximately 1.4 (Peng et al., 2024).

The crude protein content of SBP ranges from approximately 15% (dry matter) (Nour et al., 2021) to approximately 21% (dry matter) (Kaminskytė et al., 2025). Essential amino acids account for approximately 38% of the total amino acid fraction, with leucine identified as a predominant component (Peng et al., 2024), highlighting the retained nutritional value of the pomace.

Dietary fiber represents the major fraction of SBP, reaching approximately 64 g/100 g dry matter (Kaminskytė et al., 2025). This fraction consists predominantly of insoluble dietary fiber (approximately 59 g/100 g dry matter), while soluble fibre contributes approximately 5 g/100 g dry matter (Kaminskytė et al., 2025). The high fibre content underlines its structural complexity and functional potential.

SBP also contains considerable amounts of ascorbic acid (approximately 100 mg/100 g dry matter) and high levels of total polyphenols, exceeding 2000 mg GAE/100 g dry matter depending on cultivar and drying conditions, along with notable antioxidant activity (Stanciu et al., 2023). Organic acids, including malic and quinic acids, have also been identified within the pomace matrix (Suo et al., 2025). Furthermore, the presence of carotenoids contributes to the characteristic colour and antioxidant functionality of the material (Hussain et al., 2021).

Sea buckthorn pomace (SBP) contains a wide range of bioactive compounds originating from the berries, such as phenolic acids (gallic, protocatechuic, *p*-coumaric, ferulic, and chlorogenic acids), flavonols (isorhamnetin, quercetin, and kaempferol), flavan-3-ols, and polymeric procyanidins (Singh et al., 2024). These compounds are largely responsible for the high antioxidant capacity reported for sea buckthorn derivatives, as demonstrated by various in vitro assays, including DPPH (2,2-diphenyl-1-picrylhydrazyl), ABTS (2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)), FRAP (ferric reducing antioxidant power), and ORAC (oxygen radical absorbance capacity). In addition to polyphenols, pomace retains dietary fibre, carotenoids, tocopherols, essential fatty acids, vitamins, and minerals, which further enhance its nutritional value.

The biological activities associated with these bioactive constituents support the functional potential of sea buckthorn pomace. Therefore, sea buckthorn pomace should not be regarded merely as industrial waste but rather as a promising functional ingredient with considerable potential for application in functional foods, nutraceutical formulations, and natural antioxidant systems (Singh et al., 2024). In addition, the phytochemical profile of sea buckthorn pomace includes other bioactive classes such as carotenoids, triterpenes, unsaturated fatty acids, vitamins, and other isoprenoid-related compounds, further expanding its chemical complexity (Peng et al., 2024). These phytochemicals are linked to strong antioxidant and antimicrobial properties. In particular, flavonoids and other phenolic constituents contribute to the inhibition of undesirable microorganisms through mechanisms such as interference with nucleic acid synthesis, disruption of cell membrane integrity, and modulation of microbial energy metabolism. Moreover, polyphenolic compounds may interact with proteins to form complexes, which can reduce proteolytic activity and subsequently limit the formation of ammonium nitrogen during fermentation processes (Peng et al., 2024). The presence of these phytochemicals not only enhances the preservative potential of sea buckthorn pomace but also supports its application as a natural functional additive with protective effects against oxidative degradation and microbial spoilage (Peng et al., 2024). This diverse phytochemical composition contributes to the strong antioxidant potential of sea buckthorn pomace and supports its relevance as a functional ingredient in food and nutraceutical applications. These findings emphasize complementary aspects of the phytochemical profile of sea buckthorn by-products.

The study conducted by Sajfrtová et al. (2010) investigated the lipid fraction of sea buckthorn seeds, highlighting the presence of phytosterols, particularly β-sitosterol, which accounted for 57-76% of the total sterol content. Supercritical CO_2 extraction resulted in higher β-sitosterol concentrations compared to conventional Soxhlet extraction, emphasizing the seed oil fraction as a valuable source of bioactive sterols with potential hypocholesterolemic and anti-inflammatory effects (Sajfrtová et al., 2010).

In addition, Sławińska et al. (2023) analyzed the polar phytochemical profile of sea buckthorn seed extracts and reported a broad spectrum of flavonoids, mainly glycosides of isorhamnetin, kaempferol, and quercetin, as well as proanthocyanidins, catechin, and triterpenoid saponins. The total flavonoid content exceeded 150 mg/g in non-roasted seeds, confirming that the phenolic fraction represents a major group of bioactive compounds in the defatted seed matrix (Sławińska et al., 2023). These findings indicate that sea buckthorn seeds possess a dual phytochemical profile, consisting of a sterol-rich lipid fraction and a phenolic-dominant polar fraction, depending on the extraction method applied.

2. Sea buckthorn pomace as a functional food ingredient

The increasing interest in sustainable food systems has encouraged the use of fruit processing by-products as valuable ingredients in new product development. In this context, sea buckthorn pomace represents an important resource due to its significant content of bioactive compounds. Reintroducing sea buckthorn pomace into the production chain represents an effective strategy for reducing environmental burdens and improving the overall efficiency of resource utilization. The valorization of such fruit processing residues provides a sustainable alternative to conventional waste disposal methods, transforming secondary streams into valuable raw materials. Through this approach, agro-industrial by-products can be converted into functional ingredients and high-added-value products applicable in the food, cosmetic, and pharmaceutical sectors (Šalaševičienė et al., 2025).

Figure 3 provides an overview of the functional applications of sea buckthorn pomace across different food product categories.

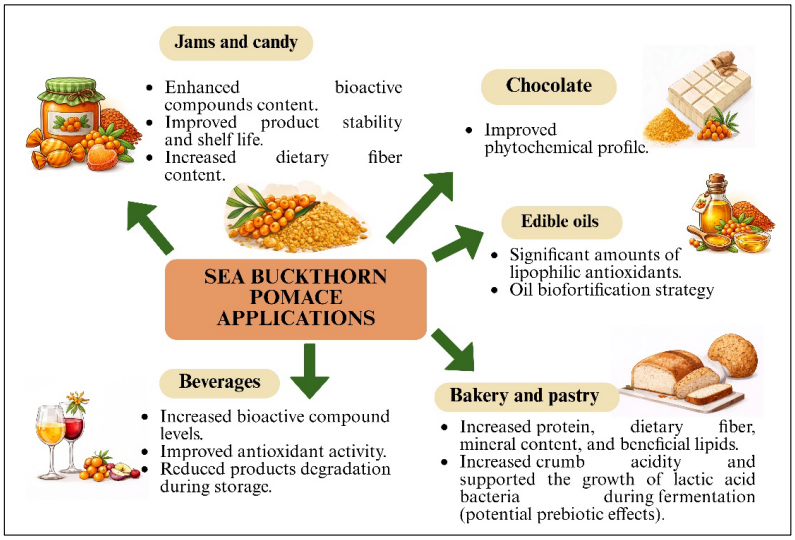

Figure 3. Functional applications of sea buckthorn pomace in food products (created in BioRender, https://BioRender.com, accessed in 25.03.2026)

2.1. Integration of sea buckthorn pomace in jelly and candy formulations

In the context of increasing consumer demand for clean-label products and natural ingredients, traditional preservation methods have gained renewed importance within the modern food industry (Urooj, 2021). Beyond preservation, producing fruit-based concentrates is a strategic way to maximize the use of fruit processing by-products. These products are valued for their sensory qualities and concentrate nutrients and beneficial compounds from the original fruit. The production of jellies and soft candies represents an important industrial application for fruit by-products. These products are developed based on the high-solids, high-acid principle, which ensures both stability and safety (Urooj, 2021).

According to Covaliov et al. (2025), the incorporation of dried SBP into quince-based jelly products provides both nutritional and functional advantages. From a nutritional perspective, the addition of pomace increased the content of carbohydrates, proteins, and minerals due to its intrinsic composition (approximately 13% protein and nearly 10% dietary fiber). The enrichment also contributed valuable bioactive compounds, particularly phenolics, resulting in enhanced antioxidant capacity of the jellies. The radical scavenging activity (DPPH assay) reached values above 90%, while hydrogen peroxide inhibition capacity also improved, demonstrating the significant antioxidant contribution of sea buckthorn pomace. From a functional standpoint, the high fiber content of the pomace positively influenced gel structure and texture. Its water-holding capacity contributed to increased firmness and chewiness of the jelly matrix while maintaining water activity below critical safety thresholds. Moreover, naturally occurring organic acids from the SBP enhanced titratable acidity and intensified the sensory profile. Formulations containing 1-2% SBP showed the most balanced combination of texture, taste, and overall acceptability (Covaliov et al., 2025).

Recent research shows that sea buckthorn juice and its by-products can be effectively incorporated into nutraceutical formulations. Lele et al. (2018) developed chewing candies enriched with sea buckthorn juice and by-products, demonstrating their antimicrobial and antioxidant potential. Both showed inhibitory activity against several pathogenic bacteria and significantly increased the total phenolic content and antioxidant capacity of the final product. The addition of by-products improved functional properties, confirming their suitability as value-added ingredients in sustainable food systems.

2.2. Integration of sea buckthorn pomace in chocolate formulations

Murariu et al. (2025) investigated the valorisation of sea buckthorn by-products obtained after juice extraction, with a particular focus on their incorporation into white chocolate as a strategy for developing a functional food product. The findings demonstrated that the addition of sea buckthorn fruit components, including pomace, to chocolate formulations provides significant nutritional and functional advantages, which may be extended to other confectionery systems enriched with sea buckthorn matrices. The incorporation of sea buckthorn by-products markedly increased the concentration of bioactive compounds in the final product. Higher inclusion levels were associated with elevated contents of total carotenoids, β-carotene, lycopene, vitamin C, flavonoids, and total phenolics. Antioxidant activity, including ABTS radical scavenging capacity, increased proportionally with the concentration of added material. In addition, mineral composition was enhanced, with enriched samples showing higher levels of calcium, magnesium, sodium, and phosphorus. Using by-product powder also increased protein and fat levels compared to formulations with only sea buckthorn juice.

From a technological perspective, the incorporation of sea buckthorn by-products influenced the textural and structural properties of the white chocolate matrix. Moderate inclusion levels improved cohesiveness and contributed to structural reinforcement, whereas higher concentrations reduced rigidity and hardness, resulting in softer products. Colour parameters were significantly affected by the presence of natural pigments, particularly carotenoids, leading to increased redness and distinct visual differentiation. Moreover, the enriched formulations remained stable throughout storage, indicating good functional integration of the pomace within the confectionery system (Murariu et al., 2025).

The incorporation of sea buckthorn pomace, either full-fat or defatted, into white chocolate provides significant nutritional and functional benefits (Murariu et al., 2024). The addition of pomace powder markedly increased the concentration of bioactive compounds, particularly carotenoids (β-carotene and lycopene), vitamin C, and total polyphenols. Antioxidant activity, including ABTS radical scavenging capacity, increased proportionally with pomace concentration, with the highest values recorded at a 15% inclusion level.

The full-fat pomace enhanced lipid content and fat-soluble bioactives such as carotenoids, whereas the defatted variant promoted higher polyphenol levels and stronger antioxidant capacity. Mineral composition was also improved, with enriched samples exhibiting increased calcium and magnesium levels, and in some formulations, elevated phosphorus content. Concerning technological properties, sea buckthorn pomace positively influenced rheological and textural parameters. At a 15% addition level, samples demonstrated greater firmness, shear force, cohesiveness, and gumminess compared to the control. The presence of natural pigments significantly altered colour characteristics, increasing brightness and redness and thereby enhancing visual appeal. A slight reduction in pH was observed with increasing pomace concentration, contributing to the distinct functional profile of the enriched products.

These findings demonstrate that sea buckthorn pomace can be effectively utilized as a multifunctional ingredient in chocolate formulations, improving antioxidant potential, mineral composition, and structural properties while supporting sustainable by-product valorisation (Murariu et al., 2024).

2.3. Integration of sea buckthorn pomace in beverage formulations

The upcycling of sea buckthorn pomace into beverage formulations represents an innovative strategy in sustainable product development. The utilization of this by-product through controlled fermentation enables the production of a low-alcohol (approximately 3% ethanol), effervescent beverage rich in phenolic antioxidants, thereby contributing to waste valorization and the development of functional products (Gatlan et al., 2020). However, current technological challenges, such as the tendency to sedimentation and astringency caused by tannins, require further research to optimize the stability and palatability of the finished product (Zhu et al., 2025).

The study conducted by Furulyas et al. (2024) highlights the valorization of sea buckthorn pomace (SBP) as a functional ingredient, emphasizing its potential to transform an agro-industrial by-product into a value-added resource. Although the bioactive properties of SBP are recognized, its antimicrobial potential remains insufficiently explored in the scientific literature. In this context, the authors aimed to investigate the antioxidant and antimicrobial characteristics of the pomace when incorporated into apple juice. Their findings, supported by the monitoring of total polyphenol content and microbial dynamics during storage, demonstrate that SBP contributes not only to improving the nutritional quality of the beverage but also to enhancing its microbiological stability, indicating a potential natural preservative effect. Another study evaluated the enrichment of sea buckthorn juice with different concentrations of dried sea buckthorn pomace (0.5-2%) and assessed physicochemical parameters, β-carotene content, total polyphenols, antioxidant capacity (FRAP), color stability, and storage behavior over 14 months. The results showed that adding pomace increased bioactive compounds and antioxidant activity while slowing their degradation during storage.

In addition, Rentsendavaa et al. (2021) investigated the stability of carotenoids and phenolic compounds in sea buckthorn (*Hippophae rhamnoides* L.) juice during storage, focusing specifically on the effect of sea buckthorn pomace addition. Juice samples were enriched with 0.5%, 1%, and 2% dried sea buckthorn pomace and stored at room temperature for 14 months. The study evaluated changes in total polyphenol content, antioxidant capacity (FRAP), β-carotene concentration, soluble solid content, pH, and colour parameters over the storage period.

The results showed that sea buckthorn pomace addition increased the initial β-carotene content and enhanced the antioxidant capacity of the juice in a dose-dependent manner. Although degradation of polyphenols and antioxidant activity occurred during storage, samples containing higher levels of pomace exhibited smaller reductions in bioactive compounds. Furthermore, a strong positive correlation between total polyphenols and antioxidant capacity confirmed the significant contribution of phenolic compounds to the overall antioxidant properties. The findings of the study demonstrate that sea buckthorn pomace addition improves the functional quality and storage stability of sea buckthorn juice.

2.4. Integration of sea buckthorn pomace in bakery and pastry formulations

The valorization of sea buckthorn pomace through its incorporation into bakery formulations represents a sustainable approach to converting this by-product into a functional ingredient with added nutritional value. Its inclusion in cereal-based products not only enhances the overall composition but also introduces technological considerations related to thermal processing. Baking is essential for developing desirable sensory attributes, ensuring microbial safety, and extending shelf life; however, it may also promote the formation of acrylamide through Maillard reaction pathways. Given the increasing regulatory attention and the need to comply with established benchmark levels, strategies to mitigate acrylamide formation are required (Ciesarová et al., 2023). In this context, the high L-asparagine content of sea buckthorn pomace makes it a potential contributor to acrylamide formation. To address this challenge, commercial asparaginase was applied to the pomace prior to drying and its incorporation into nutritionally enriched wholegrain cereal biscuits, thereby enabling its safe use while maintaining product quality and regulatory compliance (Ciesarová et al., 2023).

Recent research has explored incorporating sea buckthorn pomace into bakery products, showing that its technological and nutritional effects depend on the cereal matrix and processing conditions.

Wirkijowska et al. (2025) evaluated the use of sea buckthorn pomace in wheat bread fortification. Their findings showed that its inclusion improved the nutritional composition of bread by increasing protein, dietary fibre (particularly the insoluble fraction), mineral content, and beneficial lipids, while slightly lowering the caloric value. Although higher substitution levels negatively influenced dough stability, loaf volume, and crumb softness,

moderate additions (3–6%) achieved a suitable balance between enhanced nutritional value and acceptable technological and sensory properties. Overall, the study supports the sustainable valorization of sea buckthorn pomace as a clean-label ingredient aligned with circular economy principles, enabling the production of nutritionally improved bakery products without significantly compromising consumer acceptance at appropriate inclusion levels.

In contrast, Banach et al. (2024) investigated sea buckthorn pomace flour obtained as a by-product of juice and oil production and its application in rye bread formulated with sourdough fermentation. The incorporation of sea buckthorn pomace flour (SBPF) at moderate levels (approximately 10–15%) provided both nutritional and functional benefits. SBPF contributed substantial amounts of dietary fibre, lipids rich in bioactive fatty acids, protein, and phytochemicals, including polyphenols and carotenoids. Its addition increased crumb acidity and supported the growth of lactic acid bacteria during fermentation, suggesting potential prebiotic effects. The natural pigments intensified the crumb colour, reflecting the presence of carotenoid compounds associated with antioxidant activity. Furthermore, SBPF improved dough and bread yield, reduced baking losses, and enhanced water retention due to its high fibre content. At a 10% substitution level, loaf volume increased compared to the control, indicating improved gas retention and fermentation performance. However, higher inclusion levels (≥15-20%) adversely affected loaf volume and structure, demonstrating that excessive fibre can weaken the dough matrix. These studies confirm the significant potential of sea buckthorn pomace as a value-added ingredient in bakery formulations. Nevertheless, the optimal level of incorporation depends strongly on the type of flour, the technological process, and the structural characteristics of the final product. While wheat bread shows greater sensitivity to higher substitution levels, rye sourdough bread allows for more substantial incorporation, resulting in enhanced nutritional benefits and stronger alignment with sustainability and circular economy strategies.

According to Ciesarová et al. (2023), the incorporation of sea buckthorn pomace (SBP) into whole-grain biscuits offers significant nutritional benefits, as the pomace retains a considerable amount of bioactive compounds even after juice extraction. SBP contributes polyphenols, flavonoids, carotenoids, dietary fibre, vitamins, unsaturated fatty acids, essential amino acids, and minerals, thereby increasing the overall nutritional value of cereal-based products. The inclusion of 10% SBP enhances the concentration of health-promoting components while simultaneously supporting circular economy principles through by-product valorization. The study further demonstrates that enzymatic treatment of SBP effectively reduces acrylamide formation in biscuits. Given the naturally high free asparagine content of sea buckthorn, a major precursor of acrylamide, the application of asparaginase significantly decreases asparagine levels prior to baking. Consequently, biscuits formulated with treated SBP exhibit substantial reductions in acrylamide content, up to 64% in wheat biscuits and 35% in rye and triticale formulations, compared to those containing untreated pomace. Importantly, this mitigation approach does not compromise technological quality, as texture, spread ratio, and sensory-relevant attributes remain within acceptable ranges. Thus, sea buckthorn pomace serves as both a nutritional enhancer and, when appropriately processed, a safety-oriented ingredient that contributes to limiting the formation of heat-induced contaminants.

2.5. Integration of sea buckthorn pomace into edible oils for bioactive enrichment

In recent years, the use of certain synthetic antioxidants has been limited due to concerns regarding their potential toxic and carcinogenic effects; consequently, foods enriched with natural antioxidants have gained increasing global attention (Liu et al., 2021).

Vegetable oils are widely consumed and serve as efficient carriers for lipophilic bioactive compounds. However, many refined edible oils naturally contain low levels of carotenoids, limiting their intrinsic antioxidant capacity. Therefore, enrichment strategies aimed at enhancing oxidative stability and nutritional value have received increasing attention.

Integration of sea buckthorn pomace into edible oils for bioactive enrichment represents a promising strategy. The sea buckthorn pomace remaining after juice extraction retains significant amounts of lipophilic antioxidants, particularly carotenoids, representing an underutilized source of bioactive molecules that can be efficiently incorporated into lipid-based systems. These compounds are of considerable interest due to their antioxidant activity, coloring properties, and potential health-promoting effects, making sea buckthorn pomace a valuable raw material for functional ingredient development.

Chemat et al. (2012) investigated the direct enrichment of edible oils with carotenoids recovered from sea buckthorn pomace using ultrasound-assisted extraction. Sunflower, rapeseed, olive, and soybean oils were used both as final products and as extraction media, eliminating the need for organic solvents. Process optimization via response surface methodology showed that controlled sonication power and moderate temperatures significantly enhanced carotenoid transfer into the oil matrix. Compared to conventional maceration, ultrasound increased carotenoid concentration and drastically reduced extraction time, demonstrating the efficiency and feasibility of this solvent-free oil enrichment using sea buckthorn by-products and highlighting new perspectives for sustainable valorization in functional oils development**.**

An additional relevant contribution in the field of sea buckthorn by-product valorization was reported by Patra et al. (2022), who investigated microwave-assisted extraction (MAE) as an alternative to conventional Soxhlet extraction for obtaining bioactive compounds from sea buckthorn pomace and seeds. Both low-polarity (n-hexane) and medium-polarity (ethanol) solvents were evaluated, with the objective of maximizing extraction yield and antioxidant recovery. The study demonstrated that microwave processing significantly enhanced extraction efficiency compared to the traditional method, particularly when ethanol was used as solvent under optimized conditions, at 80°C and 150 W microwave power. The highest extraction yield was obtained for pomace using microwave-assisted ethanol extraction, substantially exceeding that achieved by Soxhlet extraction under similar solvent conditions. Moreover, the extracts obtained via MAE exhibited strong antioxidant properties, as confirmed by radical scavenging assays. In addition, when incorporated into edible oil systems, the sea buckthorn extracts demonstrated oxidative stability comparable to that of synthetic antioxidants, indicating their potential as natural alternatives for oil stabilization. These findings confirm that microwave-assisted extraction efficiently recovers antioxidant-rich fractions from sea buckthorn by-products, supporting their use in stabilizing and enhancing edible oils.

An additional application of sea buckthorn pomace valorization was reported by Bhimjiyan et al. (2021), who investigated the enrichment of cold-pressed flaxseed oil with carotenoids extracted from *Hippophae rhamnoides* pomace using ultrasound-assisted extraction. Flaxseed oil, although recognized for its high omega-3 fatty acid content and functional properties, naturally lacks carotenoids, which are important contributors to antioxidant activity and oxidative stability. Therefore, the incorporation of sea buckthorn-derived carotenoids represents a strategy to enhance both the nutritional and technological quality of the oil. The process was optimized using a statistical experimental design to maximize carotenoid transfer into the oil phase. Under optimized conditions, involving controlled sonication time, feed-to-oil ratio, and amplitude, a significant increase in carotenoid concentration was achieved in the enriched flaxseed oil. Compared to conventional extraction, ultrasound treatment resulted in substantially higher carotenoid incorporation while reducing processing time and eliminating the need for organic solvents. The enriched oil also exhibited improved radical scavenging activity and enhanced physicochemical stability. The study shows that ultrasound-assisted enrichment of flaxseed oil with sea buckthorn pomace carotenoids is an efficient, eco-friendly method, enhancing nutritional value and enabling applications in functional foods, nutraceuticals, and dietary supplements.

CONCLUSIONS

Sea buckthorn pomace is a valuable food industry by-product with significant nutritional and phytochemical potential. Rich in polyphenols, flavonoids, carotenoids, dietary fibre, vitamins, minerals, and bioactive lipids, it exhibits notable antioxidant and antimicrobial properties. Reviewed studies confirm that appropriate processing strategies, such as enzymatic treatments and controlled incorporation levels, can optimize its functional performance while preserving technological quality in final products. The integration of sea buckthorn pomace into different food systems such as beverages, bakery products, chocolate, jam and jelly, confectionery and edible oils, demonstrates its versatility as a functional ingredient. In addition to improving nutritional value, its incorporation may contribute to enhanced product stability, extended shelf life, and, in some applications, improved microbiological safety. However, the technological effects depend strongly on the formulation, processing conditions, and level of addition, highlighting the need for optimized product development strategies. Moreover, the valorization of sea buckthorn pomace supports sustainable production models by reducing food waste and promoting the efficient use of agro-industrial residues. This approach aligns with circular economy principles and contributes to the development of clean-label and value-added functional foods. Future research should further investigate bioavailability, consumer acceptance, scalability of processing technologies, and the long-term stability of bioactive compounds in complex food matrices to fully exploit the potential of sea buckthorn by-products.

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