

Review

Exploitation of Sea Buckthorn Fruit for Novel Fermented Foods Production: A Review

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Abstract: Sea buckthorn fruit is abundant with essential nutrients and bioactive substances, yet it remains less sought after. Therefore, it is valuable to explore new ways of sea buckthorn fruit processing, which can boost consumer acceptance of sea buckthorn fruit and also lead to formulation of new functional foods. In the presented review, we summarize studies focused on development of foods utilizing sea buckthorn fruit or its components and bacterial food cultures. Firstly, we discuss the impact of malolactic fermentation on content and profile of organic acids and polyphenols of sea buckthorn fruit juice. During this process, changes in antioxidant and sensory properties are considerable. Secondly, we address the role of sea buckthorn fruit and its components in formulating novel probiotic dairy and non-dairy products. In this regard, a synergic effect of prebiotic material and probiotic bacteria against pathogens is distinguished. Overall, the potential of sea buckthorn fruit as a botanical ingredient for application in novel foods is highlighted.

Keywords: lactic acid bacteria; malolactic fermentation; novel food; probiotic; sea buckthorn fruit



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1. Introduction

Sea buckthorn fruit is a rich source of many nutrients and health promoting substances. The most represented are polyphenols, ascorbic acid, carotenoids, tocopherols [1–3], and compounds belonging to the vitamin B complex, as well as minerals [4] and fatty acids [5]. It can be said that sea buckthorn berries can provide a comprehensive supply of compounds necessary for human nutrition. In that sense, content of multiple nutrients is superior when compared to other common fruits such as orange or peach [4].

Among 79 behavioral, environmental and occupational, and metabolic risks studied, non-communicable diseases, mainly cardiovascular and circulatory diseases, contribute the most to disability-adjusted life years. High systolic blood pressure, high fasting plasma glucose, high BMI, and high total cholesterol contribute greatly to the development of non-communicable diseases. Changes in human nutrition can help minimize various risk factors leading to chronic diseases; for example, increased consumption of fruits, vegetables, and fiber can positively influence low-density lipoproteins and total cholesterol [6]. It has been shown that sea buckthorn berries consumption leads to the improvement of some of the risk factors mentioned. In the studies on the impact of berries intake on metabolic profile of overweight subjects, diets enriched with sea buckthorn fruit decreased serum triglycerides and very low-density lipoproteins [7] as well as improved the glycemic profile and insulin response [8].

In recent years, research has led to a plethora of studies confirming the link between oxidative stress and the development of chronic and degenerative diseases. The observation of the accumulation of free radicals leading to health issues pointed to the possibility of using antioxidants in disorder prevention and treatment [9]. High contents of polyphenols, ascorbic acid, and tocopherols contribute to the significant antioxidant properties of sea buckthorn berries. Flavonoids seem to be the most potent antioxidants considering the

strong positive correlation between flavonoids content and antioxidant activity [1,10,11]. In the studies on the effect of sea buckthorn fruit on oxidative stress, a phenolic fraction was identified as a source of beneficial compounds. The flavonoid-rich phenolic fraction inhibited plasma lipid peroxidation and plasma protein carbonylation induced by a strong oxidant [12,13]. There have also been studies confirming the cytoprotective effect of sea buckthorn flavonoids based on the prevention of cell injuries induced by oxidizing agents [14,15].

Despite nutritional potential and all health benefits offered by sea buckthorn fruit, its consumption is not widely popular, the main reason being unpalatable taste. Sea buckthorn berries are distinctive by their sourness and astringency caused by a high total acid, malic acid, and isorhamnetin glycosides content, and by a low total sugar content and sugar/acid ratio [16,17]. In the study on consumer acceptance of nine different berry fruits, sea buckthorn berries were classified into a less-liked but divisive group. They were perceived as sour, bitter, and strong, which are attributes generally disliked; however, some respondents did like sea buckthorn berries. Acceptance could be positively influenced by the bright yellow color of sea buckthorn berries, distinguishing them from other berries, which are characterized by a dark or red color [18]. Similarly, in the study comparing consumer acceptance of five supplemented beverages containing 80% of individual fruit juices, sea buckthorn beverages gained the lowest rating of consumer acceptance and willingness to purchase. The reason was their sour taste and odor perceived as unpleasant [19].

To increase the consumer acceptance of sea buckthorn fruit, it is useful to explore new ways of its processing. Formulation of new types of foods containing sea buckthorn fruit not only makes intake of the fruit more convenient, but also contributes to the expansion of the health-promoting food range. Particularly appealing is altering fruit juice by malolactic fermentation or incorporation of fruit and its components into probiotic products. This way, novel fermented and probiotic foods can be prepared. Fermented and probiotic foods are deeply rooted in human diet all over the world. Inclusion of microorganisms in food production can contribute to preservation, improve sensory attributes, change nutritive and bioactive properties, and help maintain and restore human gut microbiota. While there are many traditional fermented dairy, meat, cereal, legume, and vegetable or fruit products, fermented food has recently regained popularity, especially in the West, due to its health-promoting potential [20].

In this review, we discuss whether sea buckthorn fruit or its components can be used as ingredients in novel fermented and probiotic foods. The ultimate goal is to newly propose sea buckthorn fruit as a botanical food ingredient that offers health benefits to humans when consumed regularly. To achieve this, we present an overview of studies on sea buckthorn fruit utilization in novel foods and review benefits, challenges, and solutions of sea buckthorn fruit application in food production.

2. Fermented Non-Probiotic Beverages

Over the past few years, many studies have been conducted, focusing on the use of lactic acid bacteria metabolism in the field of juice processing. Fermentation of juices leads to products with improved parameters compared to the original material. For example, antioxidant activity was increased as a result of fermentation in numerous berry juices, such as blueberry [21,22], blackberry [22], elderberry [23], and black chokeberry juice [24]. Additionally, the enriched volatile profiles of elderberry [25] and apple juice were studied [26,27]. Other benefits of fermented juices can be prolonged shelf life and increased consumer acceptance, as shown in a study on dragon fruit juice fermentation [28]. In terms of bacteria treatment application in the production process, sea buckthorn juice remains an under-studied material. However, it seems that the fermentation process can enhance its bioactivity and organoleptic properties, as addressed in the next sections.

2.1. Malolactic Fermentation

Malolactic fermentation induced by metabolism of lactic acid bacteria is commonly applied in the wine industry and it is particularly necessary in red wine production. Traditionally, *Oenococcus oeni* is used, although other lactic acid bacteria, especially *Lactobacillus plantarum*, are being increasingly studied and introduced to the processes of winemaking [29]. Enzymatic decarboxylation of L-malic acid into L-lactic acid as result of lactic acid bacteria metabolism is observed in challenging mediums in order to increase pH value, so that exposure of bacteria to stress is reduced [30,31]. Sea buckthorn juice contains high amounts of organic acids, among which malic acid is most represented and its total monosaccharide content is low. Accordingly, pH is typically below a value of 3 and the sugar/acid ratio is often below a value of 1 [32,33]. All of these parameters make sea buckthorn juice a suitable substrate for malolactic fermentation. Thus far, three studies on the subject of malolactic fermentation of sea buckthorn juice were conducted, as listed in Table 1.

Table 1. Summary of studied fermented beverages containing sea buckthorn juice.

Material	Bacteria	Observed Benefits	Reference
mixture of sea buckthorn juice and water in ratio 1:1	<i>Oenococcus oeni</i>	malolactic fermentation, improved sensory attributes	[34]
sea buckthorn juice	<i>Lactobacillus plantarum</i> (four strains), <i>Oenococcus oeni</i> (three strains)	malolactic fermentation	[24]
sea buckthorn juice, mixture of sea buckthorn juice and apple juice in ratio 1:1	<i>Lactobacillus plantarum</i> (five strains), <i>Lactobacillus plantarum</i> subsp. <i>argenteratensis</i> , <i>Oenococcus oeni</i>	malolactic fermentation, enhanced antioxidant activity	[35]

Tiitinen et al. [34] fermented sea buckthorn juice mixed with water with a ratio of 1:1 for 72 h at 28 °C using unadapted *Oenococcus oeni* cells at a density of 9 log CFU·mL⁻¹. After a 24 h-long fermentation, the malic acid content decreased by 80% and pH increased from 2.8 to 3.1. Prolonged fermentation had only a minor effect on the malolactic reaction. The fermentation did not affect the monosaccharide and ascorbic acid contents.

Markkinen et al. [24] fermented pure sea buckthorn juice for 72 h at 30 °C using four different strains of *Lactobacillus plantarum* and three different strains of *Oenococcus oeni*. Contrary to the study mentioned previously, none or low production of lactic acid in the fermentation process with *Oenococcus oeni* strains was recorded. They indicated the use of lower cell density as a possible reason. Regarding *Lactobacillus plantarum* strains, three of them showed malolactic conversion. *Lactobacillus plantarum* DSM 10492 converted 100% of malic acid, while total monosaccharides did not change. This led to an increase in pH from 2.86 to 3.13 and an increase in the sugar/acid ratio from 0.89 to 1.24. In this study, the effect of pectinolytic enzyme treatment of sea buckthorn juice was also studied. However, the conclusions are not clear, as some *Lactobacillus plantarum* strains performed malolactic conversion better in treated juice and some in untreated juice.

Finally, Tkacz et al. [35] monitored the malolactic fermentation of pure sea buckthorn juice, and a mixture of sea buckthorn juice and apple juice with a ratio of 1:1 for 72 h at 30 °C using five different strains of *Lactobacillus plantarum*, a strain of *Lactobacillus plantarum* subsp. *argenteratensis*, and a strain of *Oenococcus oeni*. While fermenting pure sea buckthorn juice, *Lactobacillus plantarum* strains showed better ability to convert malic acid than the other tested bacteria. The most active was *Lactobacillus plantarum* DSM 20174, which converted 20.9% of malic acid. It was noted that similar malic acid conversion did not necessarily mean similar lactic acid increment, as other metabolic pathways using malic acid can exist. The fermentation of the sea buckthorn and apple juice mixture led to stronger malic acid reduction. In this case, *Lactobacillus plantarum* DSM 10492 performed the best, with a conversion of 75.0% of malic acid. Malolactic fermentation occurred mainly between the 48th and 72nd hour for pure sea buckthorn juice and during the first 24 h for juice mixture.

Monosaccharide content was not significantly altered at the end of the fermentation both for pure and mixed sea buckthorn juice. The total content of organic acids decreased in the case of pure sea buckthorn juice fermentation, while the sugar/acid ratio remained 0.5 for the whole process of fermentation. On the contrary, the total content of organic acids increased and the sugar/acid ratio decreased in case of mixed sea buckthorn juice.

2.2. Sensory Properties

Fermentation by lactic acid bacteria can change the taste of the substrate thanks to malolactic conversion in which the sharp taste of malic acid is replaced by the softer taste of lactic acid. Moreover, subsidiary metabolic pathways lead to a change in volatile aroma compounds [29]. Tiitinen et al. [34] executed a sensory analysis to compare organoleptic attributes between fermented and unfermented sea buckthorn juice mixed with water with a ratio of 1:1. The sensory panel consisted of 11 assessors. They observed that sourness and astringency of the juice decreased from the beginning of the fermentation while sweetness increased only after 12 h of the fermentation. However, off-odor and off-flavor described as “spoiled milk, sour milk, or yogurt-like” also increased after 12 h of the fermentation. For this reason, the duration of fermentation needs to be considered. Additionally, the effect of microbial cell removal from fermented sea buckthorn juice on its taste was studied. Overall, centrifugation of juice in order to remove cells decreased sweetness for sea buckthorn juice mixture fermented for 24 and 48 h, and increased sourness and astringency for mixture fermented for 24 h. It can be that the removed part contained monosaccharides and pulp oil, contributing to better taste.

Tiitinen et al. [36] monitored the effect of malolactic fermentation on the composition of volatile profile of fruit juice from seven varieties of sea buckthorn. They observed changes mainly in the content of ethyl esters and methyl esters of short-chain carboxylic acids. In another study by Tiitinen et al. [17], significant differences in volatile profiles were noted among unfermented juices of individual sea buckthorn varieties, which were evaluated twice within two years. While some differences in sensory attributes for the same variety were observed between evaluations in two consecutive years, overall, Chuisakaya was described as the sweetest and most fruity, and Raisa as the sourest and the most astringent. Therefore, in order to create the best product possible, it is necessary to also consider the selection of sea buckthorn variety.

Other studies did not include sensory evaluation, although Markkinen et al. [24] observed a significant reduction in malic acid content, which has a strong influence on the perception of astringency in sea buckthorn juice [16]. Additionally, they detected an increase in the sugar/acid ratio, which is a parameter positively correlated with sweetness and sourness [16,17]. Tkacz et al. [35] confirmed malic acid reduction, but in contrast with previous studies, they recorded no changes or even a decrease in the sugar/acid ratio. To draw conclusions, further research is required. Nonetheless, if we point out some of the other studies on fruit juice fermentation, such as fermentation of bergamot juice [37], pomegranate juice [38], or dragon fruit juice [28], we can find that the metabolism of lactic acid bacteria can promote consumer acceptance of products due to an improvement in organoleptic characteristics.

2.3. Antioxidant Activity

Fermentation of plant-based foods can lead to enhanced antioxidant activity of a material. There are a few mechanisms able to contribute to this outcome. Firstly, bacteria express hydrolytic enzymes, which are able to break down plant cell walls, and thus, release bounded compounds. In this way, the content of total polyphenols, which positively correlates with antioxidant properties, increases. Secondly, alteration in the profile of polyphenols needs to be considered. The activity of glucosidases leads to the conversion of glycosides to respective aglycones, which are often characterized by higher antioxidant activity. Thirdly, bacteria themselves can contribute to antioxidant activity of a substrate, in

which they grow, due to their diverse enzymatic and non-enzymatic mechanisms inhibiting the generation of reactive oxygen species [39].

Since the most abundant polyphenols in sea buckthorn juice are glycosides of quercetin, isorhamnetin, and kaempferol [2,16,24], a possibility of increased antioxidant activity due to deglycosylation should be examined. It was demonstrated that flavonoid aglycons such as quercetin have better antioxidant properties in comparison with their glycosides [40,41]. Modification of the flavonoids profile due to fermentation was observed in plant materials in the past. For example, when studying fermentation of apple juice by *Lactobacillus plantarum*, Li et al. [42] observed an increase in flavonoid aglycones quercetin and phloretin, which resulted in an enhanced antioxidant activity of the fermented juice, despite a decrease in the total phenolic and total flavonoid content. Similarly, Filannino et al. [43] observed an increase in antioxidant activity of cactus cladodes after fermentation by *Lactobacillus plantarum* in a response to increased flavonoid aglycones isorhamnetin and kaempferol content. Moreover, microbial transformation of polyphenols was shown to lead to formation of novel bioactive compounds with enhanced bioavailability when compared to initial polyphenols [44].

Markkinen et al. [24] detected no significant change in total flavonol content nor in the content of individual flavonols due to fermentation of sea buckthorn juice using *Lactobacillus plantarum*. On the other hand, the effect of pectinolytic enzyme treatment of juice was also explored in this study. It led to an increase in the hydroxybenzoic acid content, flavonols content, and aglycones isorhamnetin and quercetin content, due to their release from cell walls and polysaccharides. However, antioxidant activity was not measured in this study.

Tkacz et al. [35] determined an influence of fermentation with lactic acid bacteria on flavonols content and antioxidant activity of pure sea buckthorn juice and sea buckthorn juice and apple juice mixture. Changes in these parameters were strain-dependent, but overall, *Lactobacillus plantarum* strains performed better than *Oenococcus oeni*. The highest rise in antioxidant activity of pure sea buckthorn juice was achieved by *Lactobacillus plantarum* DSM 20174 with an increase of 25%. In the case of mixed juices fermentation, strains DSM 100813, DSM 16363, and DSM 20174, which increased the antioxidant activity by 46.6% to 51.6%, performed the best. For a few strains, no change or even a reduction in antioxidant activity was recorded. Thus, in order for a new product containing fermented sea buckthorn juice to have enhanced antioxidant properties, the selection of bacterial strain has to be considered. Finally, Tkacz et al. proved that the increase in the antioxidant activity of both fermented fruit beverages was strongly positively correlated with the flavonols content.

3. Probiotic Dairy Products

FAO and WHO [45] recognize that an intake of certain live microorganisms, included primarily in the genera *Lactobacillus* and *Bifidobacterium*, in an adequate dose can be used as a prevention and treatment of certain conditions. They can act against gastrointestinal infections, bowel disorders, allergies, and overall modulate host immunity. Similarly, the EFSA Panel [46] confirmed a positive effect of yoghurt starter culture, which consists of *Streptococcus thermophilus* and *Lactobacillus delbrueckii* subsp. *bulgaricus*, on lactose digestion.

3.1. Viability of Probiotics

In order to achieve probiotic action, it is crucial to maintain certain level of viable cells of probiotic bacteria throughout the whole shelf life of a product so that ingested microorganisms remain intact when exposed to conditions of the upper intestinal tract. The minimal necessary level of viable probiotic bacteria count is considered to be 6 log CFU in milliliter or gram of food. However, it is important to select the right combination of probiotic strains and food matrix, because losses of probiotic bacteria up to 8 log CFU·g⁻¹ during simulated digestion were observed in some cases [47]. Therefore, the addition of

sea buckthorn berries or their components must not interfere with growth of probiotics. Respectively, it is desirable for sea buckthorn fruit to enhance probiotics viability.

Selvamuthukumaran et al. [48] formulated yoghurt enriched by sea buckthorn fruit syrup, which was prepared by crushing berries, adding sugar syrup, and boiling. Yoghurt starter culture was used in the study. *Streptococcus thermophilus* and *Lactobacillus delbrueckii* subsp. *bulgaricus* counts remained above value 8 log CFU·g⁻¹ throughout 21 days of storage both at 4 °C and 15 °C.

Gunenc et al. [49] carried out a study focused on the effects of the addition of whole sea buckthorn fruit or purified sea buckthorn mucilage to yoghurt on the viability of starter yoghurt culture and probiotic strains *Lactobacillus acidophilus* and *Bifidobacterium lactis*. Both fortified samples exhibited higher *Streptococcus thermophilus* counts throughout 28 days of storage at 4 °C in comparison with control yoghurt samples. Regarding the viability of *Lactobacillus delbrueckii* subsp. *bulgaricus*, differences between yoghurt with berries and yoghurt with mucilage were noticeable. *Lactobacillus delbrueckii* subsp. *bulgaricus* showed higher counts in yoghurt with berries throughout the whole 28-day period of storage in comparison to both control and mucilage fortified yoghurt. Additionally, a negative effect of mucilage addition on viability of *Lactobacillus delbrueckii* subsp. *bulgaricus* was observed on the 28th day of storage. Nevertheless, all tested samples preserved viable cells of both starter culture bacteria in amounts above 7 log CFU·mL⁻¹ during storage time. Regarding probiotic strains, samples with sea buckthorn berries or mucilage significantly promoted viability of bacteria. The number of viable cells was above 8 log CFU·mL⁻¹ since day 7 for fortified samples, while in the case of controls, this value was exceeded only after 28 days.

Similarly, Brodziak et al. [50] designed probiotic yoghurt containing sea buckthorn fruit mousse, which was obtained by grinding the whole fruit, including seeds, and by subsequent evaporation. They used probiotic yoghurt starter culture consisting of *Lactobacillus acidophilus*, *Bifidobacterium lactis*, and *Streptococcus thermophilus*. The total number of lactic acid bacteria and the total number of *Bifidobacterium* sp. remained above a value of 7 log CFU·mL⁻¹ for both control and mousse-fortified yoghurt during 21 days of storage at 4–6 °C, with no significant differences between two types of yoghurt.

Pop et al. [51] studied the influence of a 10% addition of sea buckthorn fruit lipid fraction on viability of free *Lactobacillus casei* or *Lactobacillus casei* encapsulated in alginate. Lipid fraction obtained from crushed and centrifuged berries was rich in carotenoid and fatty acids. Firstly, they compared the effect of microwave treatment on yoghurt with free probiotics and a 10% lipid fraction, yoghurt with probiotics immobilized in alginate, and yoghurt with probiotics immobilized in alginate with a 10% lipid fraction. The results showed that the effect of encapsulation in alginate with a 10% lipid fraction led to superior protection of bacteria. Viable cells count was above 7 log CFU·mL⁻¹ even after exposure to microwave treatment inducing a temperature of 55 °C. Secondly, the survival of *Lactobacillus casei* encapsulated in alginate with or without sea buckthorn fruit lipid fraction in simulated gastrointestinal condition was studied. The outcome of this assay confirmed increased protection of bacteria when lipid fraction is added to capsules.

Terpou et al. [52] studied the effect of sea buckthorn berries addition to frozen yoghurt containing probiotic strain of *Lactobacillus casei*. The use of berries as an immobilization carrier led to an increase in the survival rate of probiotic cells. After 90 days of storage at −18 °C, the number of immobilized cells remained above 9 log CFU·g⁻¹, while the number of free cells was decreasing considerably, and at the end of storage period, it remained at a value of around 7 log CFU·g⁻¹. To assess the protective effect of sea buckthorn berries, the impact of simulated gastrointestinal conditions on the viability of free and immobilized cells was also studied. The final number of viable immobilized and free cells was 7.47 log CFU·g⁻¹ and 6.01 log CFU·g⁻¹, respectively, which reaffirmed the positive influence of the use of sea buckthorn berries in the development of probiotic frozen yoghurt.

In another study, Terpou et al. [53] investigated the effect of incorporation of sea buckthorn berries in cheese. Likewise, dried sea buckthorn berries were used as an immobilization carrier for the probiotic strain of *Lactobacillus casei* in a novel feta-type cheese

production. In comparison to the cheese produced with free probiotic strains, the cheese containing sea buckthorn berries had increased probiotic bacteria counts. Throughout the 100 days, immobilized *Lactobacillus casei* counts had a range of 9.4–7.82 log CFU·g⁻¹, while free cells had a range of 8.56–6.17 log CFU·g⁻¹. In conclusion, the usage of sea buckthorn berries as probiotics carriers was proven to be beneficial for preserving *Lactobacillus casei* cells in frozen yoghurt and cheese production.

To summarize, Gunenc et al. [49], Pop et al. [51], and Terpou et al. [52,53] confirmed the positive influence of sea buckthorn fruit or its components on the viability of probiotics in dairy products, while Brodziak et al. [50] recorded no significant effect in this regard. It seems that it is easily achievable to formulate novel foods combining the nutritional benefits of sea buckthorn and the health-promoting properties of probiotics (Table 2).

Table 2. Summary of studied probiotic dairy products containing sea buckthorn fruit or its component.

Food Product	Sea Buckthorn Material	Bacteria	Observed Benefits	Reference
yoghurt	fruit syrup	<i>Streptococcus thermophilus</i> , <i>Lactobacillus delbrueckii</i> subsp. <i>bulgaricus</i>	sufficient microbial stability and sensory attributes	[48]
	fruit, purified fruit mucilage	<i>Streptococcus thermophilus</i> , <i>Lactobacillus delbrueckii</i> subsp. <i>bulgaricus</i> , <i>Lactobacillus acidophilus</i> , <i>Bifidobacterium lactis</i>	enhanced probiotics viability	[49]
	fruit mousse	<i>Lactobacillus acidophilus</i> , <i>Bifidobacterium lactis</i> , <i>Streptococcus thermophilus</i>	sufficient microbial stability and sensory attributes, possibly increased digestibility	[50]
	fruit lipid fraction	free or encapsulated <i>Lactobacillus casei</i>	enhanced probiotics viability	[51]
frozen yoghurt	fruit	<i>Lactobacillus casei</i>	enhanced probiotics viability, improved sensory attributes	[52]
feta-type cheese	fruit	<i>Lactobacillus casei</i>	enhanced probiotics viability, enriched aroma, sufficient sensory attributes	[53]

3.2. Sensory Properties

In study on yoghurt fortified by sea buckthorn fruit syrup conducted by Selvamuthukumar et al. [48], 15 trained judges evaluated color, taste, aroma, body and texture, and overall acceptability of the product. Fresh fruit yoghurt had an overall acceptability score of 8 out of 9. As a limit for identifying an unsuitable product, a score of 6.1 was chosen. Fruit yoghurt remained acceptable for 18 days when stored at 4 °C and for 9 days when stored at 15 °C. After this, the products had increased acidity and an off-flavor started to develop.

Brodziak et al. [50] carried out a sensory analysis of yoghurt with sea buckthorn fruit mousse using 20 panelists. Evaluated parameters were color, consistency, flavor, aroma, and general acceptance. When compared to a plain yoghurt, the mousse-fortified yoghurt received statistically significantly lower scores for all evaluated parameters regardless of the time of storage. Nevertheless, the yoghurt with sea buckthorn mousse achieved a relatively high score, since all parameters scored more than 4 points out of 5.

Similarly, Terpou et al. [52] conducted a sensory analysis of frozen yoghurt enriched by sea buckthorn berries using 10 panelists. Frozen yoghurt, frozen yoghurt with free probiotics, and frozen yoghurt with probiotics immobilized on sea buckthorn berries all received high scores of preferences and were characterized by a dairy flavor, smoothness, and sweetness on a similar basis. Frozen yoghurt samples containing berries had a more pronounced citrus aroma and taste.

While formulating the novel feta-type cheese enriched by sea buckthorn berries, Terpou et al. [53] recorded that the addition of berries enriched the aroma of the cheese by the increased content of terpenes and carbonyl compounds. Regarding the sensory

evaluation by 10 laboratory members, no significant differences between samples with and without the berries were observed.

Based on this, a conclusion can be drawn that the sour taste of sea buckthorn fruit is masked in the yoghurt or cheese environment. Distinct organoleptic properties of this crop do not interfere with the possibility of formulating novel dairy products containing sea buckthorn fruit.

3.3. Microbiological and Physicochemical Stability

Selvamuthukumar et al. [48] monitored the stability of yoghurt enriched by sea buckthorn fruit syrup stored for 21 days at 4 °C and 15 °C. The fresh fruit yoghurt was free from fungi and coliforms. Yeasts and molds were detected in the fruit yoghurt on day 21 and day 6 when stored at 15 °C and 4 °C, respectively. The coliforms were detected on day 15 and day 6 when stored at 15 °C and 4 °C, respectively. Thus, it was proven that the storage of yoghurt with sea buckthorn fruit syrup under refrigerated conditions is necessary for the assurance of product safety. Additionally, Selvamuthukumar et al. monitored the stability of vitamin C, vitamin E, carotenoids, anthocyanins, and phenols. All compounds were stable and did not significantly change their amounts through the storage at both temperatures. On the other hand, the viscosity of the product decreased significantly throughout the storage period, probably due to the decreasing acidity of the product causing a reduction in the water-binding capacity of proteins.

When formulating the probiotic yoghurt with sea buckthorn fruit mousse, Brodziak et al. [50] monitored microbiological and physicochemical stability of the product stored for 21 days under refrigerated conditions with a temperature in the range of 4–6 °C. When compared to a plain yoghurt, the total bacteria count was higher in the yoghurt containing mousse on the first day. However, the fortified yoghurt showed a decreasing trend of the total bacteria count, while the plain yoghurt did not. As a result, the total bacteria count was lower for the yoghurt with mousse at later storage times. On the contrary, the fortified yoghurt contained a higher number of fungi at each evaluation. Overall, both yoghurt types met sanitary and hygienic requirements during the 21-day storage period. A microstructure analysis showed that the addition of sea buckthorn mousse led to the formation of more and bigger empty spaces in the product structure. This can increase the digestibility of the product due to a larger surface area being available for digestive enzymes. However, a larger surface area of the product also means a higher susceptibility to damaging influences. This was confirmed by the loss of the initial structure of the fortified product after 21 days of storage and the formation of a gel-like texture.

4. Probiotic Non-Dairy Products

Nowadays, it is common for probiotic foods to fall into the category of dairy products, which is not suitable for people with lactose intolerance. Therefore, it is reasonable to search for new formulations and to expand the range of probiotic products with non-dairy foods. Sea buckthorn is not sufficiently researched in this matter, but studies on other fruits pointed to the possibility of formulating probiotic non-dairy products. For example, probiotic blueberry and blackberry juices [22], orange and pineapple juices [54], pomegranate juice [55], and sweet lemon juice [56] were successfully prepared.

It was shown that sea buckthorn berries polyphenols can promote proliferation of beneficial gut microbiota included in the lactic acid bacteria group and in the genera *Bifidobacterium*, and *Bacteroides*, and thus, act like prebiotic material [57]. While further research is needed, this assumption is in agreement with numerous studies confirming the prebiotic effect of dietary polyphenols [58]. On the other hand, the antipathogenic effects of polyphenols are well known. Various metabolites of polyphenols may be toxic against some gut bacteria, but appear to promote the growth of other gut bacteria; hence, these compounds may demonstrate antipathogenic and prebiotic effects simultaneously. It is not easy to pinpoint a particular principle of gut microbiota modulation in response to polyphenols intake. It seems that indigenous intestinal bacteria have developed greater

tolerance to dietary polyphenols and also express specialized metabolic pathways. Phenols are metabolized to a different extent by specific bacteria, and aromatic metabolites produced in this way are subsequently retained by the cell or released into the surroundings. Released metabolites may influence the growth of bacteria producing them as well as the growth of other neighboring bacteria species. Moreover, the released metabolites become accessible to other bacteria species. In this process, many phenols are metabolized by a variety of bacteria and undergo extensive biotransformation. Due to the complex composition of gut microbiota and their interactions, the mechanism behind the species-specific action of polyphenols is not determined entirely [59,60].

Swanson et al. [61], as part of The International Scientific Association for Probiotics and Prebiotics, pointed out the benefits of synbiotics—a mixture of live microorganisms and substrate selectively utilized by host microbiota that act towards the health of the host. Synbiotics can be a combination of probiotics and prebiotics; however, the synergic effect of the merged components can result in health benefits which are not induced by the individual components. For this reason, it can be fruitful to explore new ways in which health-promoting or prebiotic materials can be mixed with microorganisms, enhancing human well-being. Again, research on sea buckthorn fruit in this subject is not comprehensive. Products studied in this matter so far are listed in Table 3.

Table 3. Summary of studied probiotic non-dairy products containing sea buckthorn fruit component.

Food Product	Sea Buckthorn Material	Bacteria	Observed Benefits	Reference
soy milk	fruit syrup	<i>Lactobacillus casei</i> subsp. <i>paracasei</i>	enhanced probiotics viability, improved sensory attributes	[62]
		<i>Lactobacillus rhamnosus</i>	enhanced probiotics viability and antipathogenic activity	[63]
supplemented sea buckthorn juice		<i>Lactobacillus plantarum</i> , <i>Lactobacillus rhamnosus</i> , <i>Lactobacillus acidophilus</i> , <i>Lactobacillus casei</i>	enhanced probiotics viability and antipathogenic activity	[64]

4.1. Viability of Probiotics

Maftai et al. [62] designed beverages composed of soy milk and an addition of sea buckthorn fruit syrup up to 20%, in which *Lactobacillus casei* subsp. *paracasei* was incorporated. The higher the addition of syrup, the higher the increase in the number of viable bacteria cells during fermentation. Additionally, fermentation at 37 °C showed better results than fermentation at 30 °C. At the end of the 14-day storage at 4 °C, 11 log CFU·mL⁻¹ of *Lactobacillus casei* subsp. *paracasei* was determined for beverages with a 20% addition of syrup fermented at 37 °C. The viable cell population was above a value of 7 log CFU·mL⁻¹ for all samples. The positive effect of syrup addition was also confirmed by monitoring beverages in simulated gastric and intestinal conditions. The higher the addition of syrup, the better the achieved survival rate of probiotics. Survival of 37% and 33% of bacteria was achieved in simulated gastric juices with a 20% addition of syrup for beverages fermented at 37 °C and 30 °C, respectively. In simulated intestinal juices, the survival rate was 45% and 34% for the same beverages fermented at 37 °C and 30 °C, respectively. The study showed that soy milk with sea buckthorn fruit syrup addition can be used as a means to deliver probiotic strain *Lactobacillus casei* subsp. *paracasei*.

Sireswar et al. [63] evaluated the capability of *Lactobacillus rhamnosus* to survive in sea buckthorn juice. To create a suitable environment to maintain a sufficient amount of viable probiotic cells, sea buckthorn juice had the pH value adjusted by tri-sodium citrate and was supplemented by 4% whey protein concentrate, 4% soy protein isolate, or 2% skim milk. The value of pH for individual supplemented juices was 4.5, 3, and 2.8, respectively. During 14 days of storage at 4 °C, only whey protein concentrate-supplemented juice with the highest pH value tested maintained the number of probiotics above 8 log CFU·mL⁻¹.

Soy protein isolate-supplemented and skim milk-supplemented juice with lower pH values preserved only 4 log CFU·mL⁻¹ and 2 log CFU·mL⁻¹ of viable cells, respectively. Due to the acidic character of sea buckthorn juice, it seems that pH adjustment is necessary.

Sireswar et al. [64] conducted another similar study in which they confirmed the ability of probiotic strains of *Lactobacillus plantarum*, *Lactobacillus rhamnosus*, *Lactobacillus acidophilus*, or *Lactobacillus casei* to retain a cell population above 8 log CFU·mL⁻¹ in sea buckthorn juice supplemented with 4% whey protein concentrate or 5% malt. Similar to the study mentioned above, it was necessary to adjust pH of the juice to 4.5 to prevent probiotic cell decline. Charalampopoulos et al. [65] demonstrated that malt, whey, and barley extracts exhibit a significant protective effect on the viability of *Lactobacillus plantarum*, *Lactobacillus acidophilus*, and *Lactobacillus reuteri* during the 4 h in acidic environment with pH 2.5. The improvement of viability was correlated with maltose or glucose content.

4.2. Sensory Properties

When formulating a soy milk beverage with added sea buckthorn syrup, Maftai et al. [62] conducted a sensory analysis using 10 panelists. The color and the overall acceptance were rated better for beverages with a 20% syrup addition in comparison to lower additions. The beverage with a 5% addition achieved a lower score for texture in comparison with beverages with higher additions. Concerning flavor and taste, there were no significant differences in scores between drinks with different syrup additions. It was concluded that the 20% sea buckthorn syrup addition can improve the sensory properties of the probiotic soy milk beverage.

4.3. Antipathogenic Activity

It is known that one of the many benefits offered by probiotics is the inhibition of pathogens. In regards to polyphenols, accumulating evidence suggests that they have a species-specific effect on microorganisms. There are studies confirming the antipathogenic properties of polyphenols and also studies acknowledging positive impact of polyphenols on probiotic bacteria. Thus, a polyphenol-probiotic combination can operate in a synergistic manner. For this reason, these two antipathogenic factors can be a valuable mean to maintain healthy gut microbiota and to prevent the growth of pathogens in food matrices [44].

Sireswar et al. [63] compared the influence of sea buckthorn juice and sea buckthorn juice fortified by *Lactobacillus rhamnosus* (8 log CFU·mL⁻¹) on the growth of *Escherichia coli* (6 log CFU·mL⁻¹). Complete inhibition was achieved within 6 days of storage at 4 °C and 10 °C for probiotic juice, while non-probiotic juice did not inhibit *Escherichia coli* during 14 days of monitoring. Thus, the conclusion can be reached that probiotic strain operated as a hurdle for the growth of *Escherichia coli*.

Sireswat et al. [64] monitored the influence of addition of probiotic strains *Lactobacillus rhamnosus*, *Lactobacillus plantarum*, *Lactobacillus acidophilus*, or *Lactobacillus casei* (each 8 log CFU·mL⁻¹) on the antipathogenic properties of supplemented sea buckthorn juice. The contribution of probiotic bacteria to the inhibition of enteropathogenic *Escherichia coli*, *Salmonella enteritidis*, *Shigella dysenteriae*, and *Shigella flexneri* (each 6 log CFU·mL⁻¹) in juice was confirmed, with the activity of *Lactobacillus rhamnosus* being superior. Additionally, when comparing the influence of two different additions in sea buckthorn juice fortified by *Lactobacillus rhamnosus* on the viability of pathogenic bacteria, better inhibition was observed by malt-supplemented juice in comparison to whey protein concentrate-supplemented juice. Enteropathogenic *Escherichia coli*, *Salmonella enteritidis*, *Shigella dysenteriae*, and *Shigella flexneri* were inhibited by malt-supplemented juice in 1, 1, 1, and 4 days, respectively, while whey protein concentrate-supplemented juice inhibited these pathogens in 4, 3, 4, and 8 days, respectively. It seems that for achieving a synergic effect of sea buckthorn juice and probiotic strains against pathogenic bacteria, the selection of the right probiotic strain, supplementation, and pH adjustment needs to be considered.

5. Final Remarks

The formulation of novel foods should be aimed at improving the quality of human nutrition. Sea buckthorn fruit represents a good candidate for incorporation in food matrices in order to achieve this goal. In this regard, the biggest issue seems to be its challenging sensory attributes. As discussed in presented review, a solution is offered by malolactic fermentation of the juice and integrating sea buckthorn fruit or its components in fermented dairy products. This way, new types of fermented foods are prepared, characterized by a low degree of processing, which offers economical and nutritional advantages. Moreover, treating sea buckthorn fruit by fermentation not only deals with the palatability of the fruit but also deepens its favorable effects. In recent years, many studies on foods fermented by lactic acid bacteria have pointed to changes in the polyphenols profile. These alterations are shown to enhance the antioxidant activity of fermented material as well as increase bioavailability of bioactive compounds. Sea buckthorn fruit is rich in antioxidants, with polyphenols being the most represented. Therefore, research on their modifications due to fermentation should be carried on more intensively.

Furthermore, interactions between sea buckthorn fruit and beneficial bacteria are two-sided. Not only fermentation leads to alterations in the chemical composition of sea buckthorn fruit but the fruit also affects the probiotics. It was acknowledged that sea buckthorn fruit or its components can be a useful addition to probiotic products, dairy or non-dairy, on account of its positive influence on the viability of probiotic bacteria. Probiotic food is incorporated in diets of people throughout the world, as it is understood to be essential in maintaining a healthy gut microbiota and promoting overall health. Since sea buckthorn fruit demonstrates prebiotic properties, it should be considered in research on synergistic food matrices, combining probiotics and prebiotic material.

Although sea buckthorn fruit exploitation has some challenges and research in this topic is still insufficient, sea buckthorn fruit has the potential as a new botanical healthy food ingredient, and it is worth incorporating in novel foods. The conclusions of studies carried out so far have shed light on possibilities and benefits of sea buckthorn fruit use in fermented and probiotic foods. However, further exploration in this field is needed so that objectively suitable formulations of foods containing sea buckthorn fruit or its components can be designed.

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