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Effects of Mechanical Pressing and Drying Conditions on the Physicochemical and Sensory Properties of Sea Buckthorn Tea-Type Products

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Abstract

Sea buckthorn (*Hippophae rhamnoides* L.) juice pressing generates a substantial pomace fraction that remains underutilized despite its considerable content of bioactive compounds. This study aimed to develop tea-type products from sea buckthorn juice and pomace and to evaluate the effects of the mechanical processing option and drying method on their physicochemical and sensory quality. Frozen berries were processed using two mechanical pressing options (slow screw pressing, centrifugal pressing) to generate juice and pomace fractions, which were subsequently dried by freeze-drying (juice), infrared or convection drying (pomace) into seven product variants (a raw control, two tea cubes and four pomace strips). Dry matter content, vitamin C and total carotenoid content, water-soluble fraction of the dry matter and sensory acceptability were evaluated. Mechanical processing strongly determined fraction yield: slow screw pressing maximized juice recovery (91.75%), whereas centrifugal pressing maximized pomace yield (34.67%). Freeze-dried juice tea cubes had the highest dry matter content (up to 92.65%), vitamin C content (96.12–104.35 mg/100 g as-is, i.e., 103.7–112.8 mg/100 g DM), water-soluble fraction (above 92% of dry matter) and sensory liking scores (4–5 of 5); however, because juice was only freeze-dried and pomace only infrared- or hot-air-dried, these differences reflect both the starting material and the drying conditions. In the pomace strips, only about 10% of the dry matter was extracted into water under the infusion conditions applied (water-soluble fraction); they were low in vitamin C (3.51–6.45 mg/100 g as-is, i.e., 3.94–7.17 mg/100 g DM) and scored 1–2; among them, centrifugal-pressing strips had higher carotenoid content (14.87–14.89 vs. 8.49–8.70 mg/100 g DM) and slightly higher descriptive sensory scores, whereas the infrared (45 °C, 1.5 m/s) and hot-air (50 °C, 0.3 m/s) regimes tested on pomace did not differ significantly in the physicochemical parameters measured. As fraction and drying method were confounded, each processing route was performed once from a single raw-material batch, and soluble solids in the infusions were not standardized, the findings are comparative, the statistical comparisons describe the analysed samples only, and the sensory results are indicative; the pomace strips are unsuitable as a standalone tea raw material without further processing, e.g., milling.

Keywords: sea buckthorn; pomace valorization; mechanical pressing; drying method; tea-type products; carotenoids; vitamin C retention

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Academic Editor: Giuseppe Sortino

Received: 17 September 2026
Revised: 7 November 2026
Accepted: 17 November 2026
Published: 19 November 2026

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1. Introduction

The food industry annually produces significant amounts of by-products of fruit and berry processing—pomace, peels, seeds and similar residues—which are usually considered as production waste, although their chemical composition is often not inferior to the main raw material. The world has seen a steady transition from a linear production model to a circular economy, within which by-products of agro-processing are considered not as waste, but as a resource for obtaining value-added products [1]. This is especially relevant for industries working with berry raw materials, since it is the pomace after pressing juice or oil that remains a source of biologically active substances that are simply lost during standard processing.

Sea buckthorn (*Hippophae rhamnoides* L.) is a perennial plant of the *Elaeagnaceae* family, naturally distributed in temperate regions of Europe and Asia. Due to its high adaptability to adverse environmental conditions, nitrogen-fixing ability and significant content of biologically active compounds, sea buckthorn is considered one of the most promising crops for functional foods and nutraceuticals [2]. Sea buckthorn fruits contain a wide range of macro- and micronutrients—vitamin C, carotenoids, tocopherols, flavonoids, phenolic acids, phytosterols and polyunsaturated fatty acids, including palmitoleic acid (ω-7) at levels rarely found in plant raw materials—which together provide pronounced antioxidant, anti-inflammatory, antimicrobial and hepatoprotective properties, as well as prospects for preventing metabolic disorders such as obesity, insulin resistance and cardiovascular diseases [2,3]. The chemical composition of sea buckthorn fruits is known to vary considerably with genotype, geographical origin and cultivation conditions, which must be considered when standardizing processing technologies [4]. The fruit also yields two chemically distinct oils: a polyunsaturated seed oil and a pulp oil rich in palmitoleic acid and carotenoids. The pulp oil, rich in carotenoids, contributes to the colour and composition of sea buckthorn products; its partitioning between juice and pomace during pressing may therefore influence the quality of tea-type products [5].

After juice, concentrate and oil production, 20–30% of the processed fruit mass remains as pomace, consisting of pulp, skin and seed residues that are still underutilized in the food industry despite their high content of bioactive compounds, including residual lipids and carotenoids [5]. Fractionation studies confirm that a substantial share of phenolic compounds and antioxidant capacity remains in the defatted meal after oil extraction, together with demonstrated antiproliferative activity against colorectal cancer cells [6]. Research on pomace has focused largely on the recovery of dietary fibre [7,8]; however, sea buckthorn pomace fibre is predominantly insoluble and therefore does not pass into an aqueous infusion, so for tea-type products the water-extractable fraction is more relevant than the fibre content. Broader reviews of sea buckthorn's nutritional value confirm that both fruits and processing by-products are rich in flavonoids, phenolic acids and carotenoids relevant to functional food and beverage applications [9].

Fruit and vegetable processing residues are valued as functional additives in beverages, bakery products and snacks [10], and the main technological limitations identified are raw material variability and the need to optimize drying and standardization processes [11]. Despite this body of work on apple, grape and other fruit pomace, the use of sea buckthorn pomace specifically as a functional ingredient in finished tea-type products remains insufficiently studied.

Functional teas represent one of the most promising categories of functional products, as they can be formulated from diverse plant raw materials without complex technological operations and are increasingly viewed as an intermediate category between traditional beverages and functional foods that allows effective delivery of plant bioactive substances through the daily diet [12,13]. Sea buckthorn teas have so far been studied almost exclusively

from leaves, which are rich in phenolic compounds with high antioxidant activity [14,15], and recent work on dry concentrates and powders shows that such formats can improve the stability of bioactive components in instant beverages [16]. However, the valorization of fruit-processing fractions (juice and pomace) for tea-type products remains unexplored.

The direct incorporation of sea buckthorn by-products into food formulations has been demonstrated mainly in bakery applications, such as wheat and rye bread enriched with pomace [17,18], and in a phospholipid-stabilized functional food emulsion [19]; comparable upcycling approaches exist for other fruit pomace [20,21]. These studies are limited to enriching conventional products, whereas the use of sea buckthorn juice and pomace as standalone tea-type products has not been systematically evaluated.

The quality of such products depends on upstream processing. Different pressing principles partition the berry mass between juice and pomace, and juice yield is highly sensitive to pressing conditions [22]. The drying method, in turn, strongly affects residual moisture, vitamin C and phenolic content of sea buckthorn berries and pomace [23–25], and vitamin C and carotenoids are susceptible to thermal and oxidative degradation during drying [26]. In addition, the solids of dried juice dissolve on rehydration, whereas water-soluble components of the dry matter must be extracted from dried pomace, which affects the interpretation of the water-soluble fraction and sensory results. To our knowledge, the combined effects of pressing option and drying route on sea buckthorn juice and pomace as tea raw materials have not been compared.

We hypothesized that both the pressed juice and the pomace can be developed into tea-type products, and that the mechanical pressing option and the subsequent drying route influence their physicochemical quality and sensory characteristics. Accordingly, the aim of this study was to develop sea buckthorn tea-type products from juice (freeze-dried tea cubes) and pomace (infrared- or convection-dried strips) and to compare six processing routes in terms of dry matter, vitamin C and total carotenoid content (on an as-is and dry-matter basis), water-soluble fraction of the dry matter of the dried products and sensory acceptability of the infusions. Because juice was only freeze-dried and pomace only infrared- or convection-dried, the two formats differ in both fraction and drying method; the effects of the pressing option (within each format) and of infrared versus convection drying (within pomace) are therefore the primary comparisons.

The novelty of this study lies in evaluating the juice and pomace fractions of sea buckthorn pressing, rather than leaves, as raw materials for tea-type products and in comparing how two pressing options and drying routes affect their quality, thereby supporting by-product valorization and more resource-efficient food production.

2. Materials and Methods

2.1. Raw Material and Experimental Design

Frozen sea buckthorn (*Hippophae rhamnoides* L.) berries were used as the raw material for this study. The berries were supplied deep-frozen in 25 kg paper bags and stored at −19 °C until processing. The raw material was delivered by a company supplying plant raw materials to food production and processing enterprises, operating under a quality management system certified in accordance with LST EN ISO 9001:2015, Quality Management Systems—Requirements. Lithuanian Standards Board: Vilnius, Lithuania, 2015, and the Bio Suisse organic production standard; for confidentiality reasons, the company name is not disclosed. Prior to pressing, the berries were thawed at a temperature of 4–6 °C for 12–14 h (until a core temperature of approx. 2–4 °C was reached). All technological variants were prepared from a single batch of raw material to ensure uniform initial quality.

The research was conducted from January to March 2026 at the Department of Food and Agrotechnology, Faculty of Informatics, Engineering and Technology, Kauno Kolegija, Kaunas, Lithuania (technological processing, product development and organoleptic testing), and at the Laboratory of Plant Raw Materials Quality of the Joint Open Access Research Center of Agriculture and Forestry, Agriculture Academy of Vytautas Magnus University, Kaunas, Lithuania (physicochemical analyses).

Experimental design. Thawed berries (Code I, control) were subjected to two mechanical pressing options to obtain juice and pomace fractions. The juice obtained by slow screw pressing (Code II) and centrifugal pressing (Code III) was freeze-dried to produce tea cubes. The pomace obtained by slow screw pressing was dried by infrared (Code IV) or convection (Code VI) drying, and the pomace from centrifugal pressing was dried by infrared (Code V) or convection (Code VII) drying to yield pomace strips. Thus, six processing routes yielding two product formats were compared, together with the raw control (seven samples; Table 1; Figure 1). Because juice was only freeze-dried and pomace was only infrared- or convection-dried, the effects of the fraction and of the drying method are confounded; the unconfounded comparisons are the effect of the pressing option within each format and of infrared versus convection drying within the pomace strips. All formulations were based exclusively on sea buckthorn berries and their processing fractions (juice, pomace); no additional plant ingredients were used.

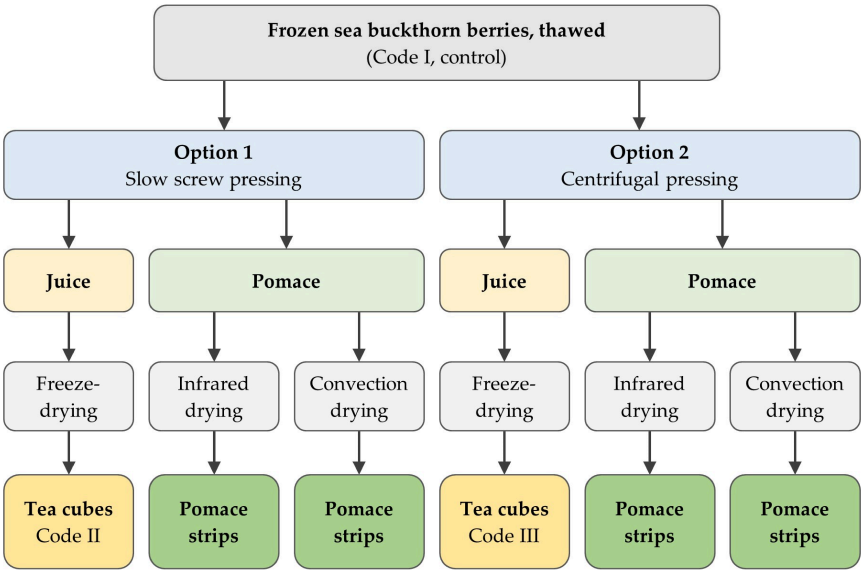

Figure 1. Scheme of the experimental design: thawed berries were pressed by slow screw pressing (Option 1) or centrifugal pressing (Option 2); the juice was freeze-dried (tea cubes, Codes II and III), and the pomace was dried by infrared (Codes IV and V) or convection (Codes VI and VII) drying (pomace strips).

Table 1. Coding of sea buckthorn tea samples analyzed in this study.

Sample Code	Product Fraction	Processing Option	Drying Method
I	Control	Raw, unprocessed sea buckthorn berries (thawed)	–
II—Tea cubes (Option 1)	Tea cubes	Juice, Option 1—slow screw mechanical pressing	Freeze-drying (lyophilization)

Table 1. *Cont.*

Sample Code	Product Fraction	Processing Option	Drying Method
III—Tea cubes (Option 2)	Tea cubes	Juice, Option 2—centrifugal pressing	Freeze-drying (lyophilization)
IV—Pomace strips (Option 1, IR)	Pomace strips	Pomace, Option 1—slow screw mechanical pressing	Infrared drying
V—Pomace strips (Option 2, IR)	Pomace strips	Pomace, Option 2—centrifugal pressing	Infrared drying
VI—Pomace strips (Option 1, conv.)	Pomace strips	Pomace, Option 1—slow screw mechanical pressing	Convection (hot-air) drying
VII—Pomace strips (Option 2, conv.)	Pomace strips	Pomace, Option 2—centrifugal pressing	Convection (hot-air) drying

2.2. Mechanical Pressing and Fraction Yield

Thawed sea buckthorn berries were processed using two juice extraction options. In Option 1 (slow screw pressing), juice was extracted using an Angel Juicer 7500 twin-gear slow juicer (Angel Juicer, Busan, Republic of Korea) at a nominal rotational speed of 82 rpm. In Option 2 (centrifugal pressing), juice was extracted using a Neumärker Juice Master Professional centrifugal juicer (Ernst Neumärker GmbH & Co. KG, Hemer, Germany) with a manufacturer-specified rotational speed of 6300 rpm. The two options differ in the mechanism of juice release: in the twin-gear juicer, the berries are crushed and squeezed between two slowly rotating gears, and the juice is released mainly by pressure-induced rupture of the cells, whereas in the centrifugal juicer the berries are rapidly disintegrated by a high-speed rotating grating blade (mechanical shearing of the cells), and the juice is separated from the pulp through a sieve basket by centrifugal force [27,28]. Each pressing option was performed once, using a separate portion of the thawed berries from the same batch. The juice and pomace fractions were collected separately and weighed, and the yield of each fraction was expressed as a percentage of the initial berry mass (Equation (1)). Pomace yield was calculated by difference and therefore includes process losses. The two options were compared in terms of the mass distribution between the fractions. Applied pressure, sieve aperture diameter and product temperature during extraction were not measured (see Section 4.9). Photographs of the fractions are given in Supplementary Figure S1.

$$\text{Fraction yield } (\%) = (m_{\text{fraction}}/m_{\text{berries}}) \times 100 \quad (1)$$

where m_{fraction} is the mass of the juice or pomace fraction (g) and m_{berries} is the initial mass of the thawed berries (g).

2.3. Drying Procedures

2.3.1. Freeze-Drying of Juice

The juice fractions obtained by slow screw pressing (Code II) and centrifugal pressing (Code III) were poured into silicone molds of equal volume (cavity 25 × 25 × 20 mm, filled with 10 mL of juice), frozen at −21 ± 1 °C, and lyophilized under vacuum using a laboratory freeze-dryer (ALPHA 1-4 LD plus, Martin Christ Gefriertrocknungsanlagen GmbH, Osterode am Harz, Germany) for 48 h to yield cube-shaped tea products ("tea cubes"). The temperature of the ice condenser of the freeze-dryer was −56 °C. The shelf temperature was maintained at +20 °C (ambient shelf conditioning) and the chamber pressure was 12 Pa (0.12 mbar). Photographs of the frozen juice and the freeze-dried tea cubes are given in Supplementary Figures S2 and S3.

2.3.2. Infrared and Convection Drying of Pomace

The wet pomace was distributed in a uniform layer (5 mm thickness, corresponding to a surface load of 0.35 g/cm^2) and dehydrated to obtain pomace strips either by infrared drying (IDO-45, Infraservis, Kyiv, Ukraine; temperature 45 ± 1 °C, radiator power density 0.8 kW/m^2, distance to material 100 mm, forced air flow 1.5 m/s) or by convection hot-air drying (Heratherm OMS60, Thermo Fisher Scientific, Langenselbold, Germany); temperature 50 ± 1 °C, air velocity 0.3 m/s. Infrared drying was applied to slow screw pomace (Code IV) and centrifugal pomace (Code V), and convection drying to slow screw pomace (Code VI) and centrifugal pomace (Code VII). The process lasted 24–28 h depending on the sample matrix and was continued until constant mass (defined as a mass change < 0.1 g over a 1 h interval, corresponding to a final moisture content approximately 10% w.b.); the long duration was due to the high initial moisture of the pomace, the layer thickness and the relatively low drying temperature selected to limit degradation of thermolabile vitamin C and carotenoids. The dried products were stored in sealed food-grade plastic packaging protected from light and oxygen at ambient temperature (~22 °C) until analysis; the time between drying and analysis was 7 days. Photographs of the dried products are given in Supplementary Figures S4 and S5.

2.4. Preparation of Infusions

For sensory evaluation and for the determination of the water-soluble fraction (Section 2.5.4), 5 g of dried product was infused in 100 mL of water preheated to 60 ± 1 °C for 5 min, followed by stirring, sedimentation and filtration through a paper filter (11 µm pore size, Whatman No. 1). The temperature of 60 °C was selected to limit the thermal degradation of vitamin C and carotenoids and to correspond to a comfortable serving temperature for sensory evaluation; the temperature at the end of infusion was 52 ± 1 °C. The same product-to-water ratio (5 g per 100 mL) was applied to all samples to allow comparison on an equal mass basis, although the moisture and composition of the samples differ; consequently, the mass of soluble components per volume of water in the infusions was not equalized (Section 4.9). In tea cubes, the freeze-dried juice solids dissolve, whereas water-soluble components of the dry matter are extracted from pomace strips; for comparability, both are expressed as the water-soluble fraction of the dry matter of the sample, i.e., of the components contained in the tea samples.

Vitamin C, carotenoids and dry matter were determined directly in the dried products (Section 2.5), not in the infusions.

2.5. Analytical Methods

2.5.1. Dry Matter

Dry matter content was determined gravimetrically in accordance with LST ISO 751:2000; Fruit and Vegetable Products—Determination of Water-Insoluble Solids. Lithuanian Standards Board: Vilnius, Lithuania, 2000. Samples (approx. 3 g) were first dried at 65 °C for 2–3 h and subsequently at 105 °C to constant mass (3–4 h defined as a mass difference ≤ 0.001 g between two successive weightings after a 1 h interval). Dry matter content was calculated from the final mass after drying at 105 °C (Equation (2)).

$$\mathrm{DM}\ (\%) = (m_{105}/m_0) \times 100 \quad (2)$$

where m_0 is the initial sample mass (g) and m_{105} is the sample mass after drying to constant mass at 105 °C (g). Dry matter was calculated separately for each replicate ($n = 2$) from the paired masses of the same portion (m_0 and m_{105}); as Equation (2) is a ratio of these two masses, the result does not depend on the absolute mass of the portion. All replicate values were retained in the calculation of the means.

2.5.2. Vitamin C

Vitamin C (ascorbic acid) content was determined by titration with a standardized 2,6-dichlorophenolindophenol (Tillmans' reagent; Merck KGaA, Darmstadt, Germany) solution (titer 0.088 mg of ascorbic acid per mL of reagent). An accurately weighed sample (approximately 5 g of homogenized control berries or approximately 2.5 g of tea cubes or pomace strips ground to a fine powder) was extracted with 100 mL of 2% (*w*/*v*) oxalic acid (Merck KGaA, Darmstadt, Germany) solution to stabilize ascorbic acid and minimize oxidation. The mixture was thoroughly mixed for 10 min and filtered through a paper filter. A 10 mL aliquot of the clear filtrate was titrated with the standardized Tillmans' reagent until a faint pink color persisted for 10–15 s. Each sample was titrated in three replicates ($n = 3$) from the same extract. The ascorbic acid content was calculated according to Equation (3) and expressed as mg per 100 g of sample (as-is basis) and per 100 g of dry matter (Equation (5)).

$$\text{Xvit C} = (\text{a} \times \text{T} \times \text{V} \times 100)/(\text{b} \times \text{m}) \quad (3)$$

where a is the volume of the Tillmans' reagent consumed in titration (mL), T is the titer of the reagent (mg of ascorbic acid per mL), V is the total volume of the extract (mL; 100 mL), b is the volume of the aliquot titrated (mL; 10 mL), and m is the sample mass (g); Xvit C is expressed in mg per 100 g of sample (as-is).

2.5.3. Total Carotenoids

Total carotenoid content was determined spectrophotometrically (UVS-2800, Labomed Inc., Los Angeles, CA, USA) at 470 nm. An accurately weighed sample (approximately 2 g of homogenized control berries or approximately 1 g of tea cubes or pomace strips) was extracted with acetone (Merck KGaA, Darmstadt, Germany) for 15 min in the dark, filtered and made up to a final volume of 100 mL. The absorbance of the extract was measured against the solvent blank in a 10 mm cuvette. The carotenoid concentration in the extract was calculated by comparison with the potassium dichromate ($K_2Cr_2O_7$; Merck KGaA, Darmstadt, Germany) standard of the classical photometric carotene method, whose optical density corresponds to a carotene concentration of 0.00416 mg/mL; the absorbance of the standard solution was taken as 1. The content was calculated according to Equation (4) and is expressed as total carotenoids (carotene equivalents) in mg per 100 g of sample (as-is basis) and per 100 g of dry matter (Equation (5)). Each sample was measured in three replicates from the same extract.

$$\text{Xcar} = (\text{A}/\text{Ast}) \times 0.00416 \times \text{V} \times 100/\text{m} = (\text{A} \times 0.00416 \times \text{V} \times 100)/\text{m} \quad (4)$$

where A is the absorbance of the extract at 470 nm, Ast is the absorbance of the potassium dichromate standard (taken as 1), 0.00416 is the carotene-equivalent concentration of the standard (mg/mL), V is the extract volume (mL; 100 mL) and m is the sample mass (g); Xcar is expressed in mg per 100 g of sample (as-is basis).

2.5.4. Water-Soluble Fraction

The infusion was prepared as described in Section 2.4 (m_{sample} = 5 g of the dried product, weighed before infusion). The insoluble residue retained on the filter was dried to constant mass at 105 ± 2 °C and weighed gravimetrically (m_1). The insoluble residue and the water-soluble fraction were calculated according to Equations (6) and (7) (Section 2.7). The water-soluble fraction thus characterizes the share of the dry matter of the dried product that passed into the infusion; the extract content of the infusions themselves was not determined. Thus, three quantities were used for each replicate: the mass of the sample taken for the infusion (m_{sample}), its dry matter content (DM, Equation (2), Table 4; determined on a

separate portion of the same product) and the mass of the dried insoluble residue (m_1). The dissolved matter was not measured directly (the dry matter of the filtrate was not determined) but was obtained by difference (Equation (7)); the water-soluble fraction therefore also includes any minor losses of solids during filtration and handling. The results are expressed on a dry-matter basis, i.e., as a percentage of the dry matter mass of the sample taken for the infusion ($m_{0,dm}$), and not of its as-is mass.

2.6. Sensory Evaluation

The sensory properties were evaluated by a panel of 30 assessors (20 female and 10 male), aged 18 to 45 years, recruited among the staff and students of Kauno kolegija Higher Education Institution. All assessors were untrained consumers. Participation was voluntary; persons with an allergy or intolerance to sea buckthorn or other berries, or with a known impairment of taste or smell, were excluded. Ethical aspects are described in the Institutional Review Board and Informed Consent Statements.

Sensory data are expressed as mean scores of the panel ($n = 30$). Only the mean score for each sample and attribute was recorded; therefore, standard deviations and statistical comparisons are not reported. The soluble solids content of the infusions was neither measured nor standardized, and individual assessor scores were not retained; the sensory results are interpreted as indicative liking scores of infusions prepared at an identical product-to-water mass ratio.

The evaluation was carried out in the sensory laboratory of Kauno kolegija in accordance with LST EN ISO 8589:2010 (sensory Analysis—General Guidance for the Design of Test Rooms. Lithuanian Standards Board: Vilnius, Lithuania, 2010), at 20 ± 2 °C, under uniform daylight-type illumination and in an environment free from extraneous odors. Infusions were prepared as in Section 2.4 and served at the temperature reached at the end of infusion (52 ± 1 °C) in odorless, transparent glass vessels labelled with random three-digit codes, in randomized order; still water was provided for palate cleansing. Each assessor evaluated all samples in a single session.

A 5-point hedonic scale (Table 2) was used. Assessors rated their liking of the infusions for: color (appearance of the infusion), aroma, taste, and mouthfeel (perceived body/consistency of the liquid, presence of particles). The evaluation followed the general principles of LST ISO 6658:2017 (Sensory Analysis—Methodology—General Guidance. International Organization for Standardization: Geneva, Switzerland, 2017) and LST EN ISO 13299:2016 (Sensory Analysis—Methodology—General Guidance for Establishing a Sensory Profile. Lithuanian Standards Board: Vilnius, Lithuania, 2016). Results are reported as mean scores for each attribute.

Table 2. Five-point hedonic scale used for sensory evaluation of tea samples.

Score	Sensory Interpretation
1	very bad
2	bad
3	moderate
4	good
5	very good

2.7. Calculations

Vitamin C and carotenoid contents were expressed on an as-is and a dry-matter basis:

$$X_{dm} = X_{as\text{-}is}/(DM/100) \quad (5)$$

where X_{dm} is the content on a dry-matter basis, $X_{as\text{-}is}$ is the content in the sample as analyzed (mg/100 g), and DM is the dry matter content (%) determined according to Equation (2).

The insoluble residue was calculated as:

$$\text{Insoluble residue (\% DM)} = (m_1/m_{0,dm}) \times 100 \quad (6)$$

where m_1 is the mass of the dried insoluble residue (g) and $m_{0,dm}$ is the dry matter mass of the sample used for the infusion (g), $m_{0,dm} = m_{sample} \times DM/100$, which excludes the effect of moisture. Here, m_{sample} is the actually weighed mass of the sample taken for the infusion (g; nominally 5 g) and DM is the dry matter content of the product (%) determined according to Equation (2) (Table 4). Because the residue is related to the dry matter of the same weighed sample, small deviations of its mass from 5 g do not affect the result. The water-soluble fraction of the dry matter (solubility of the components contained in the sample) was then calculated as:

$$\text{Water-soluble fraction (\% DM)} = 100 - \text{Insoluble residue (\% DM)} \quad (7)$$

2.8. Statistical Analysis

All technological variants were prepared from a single batch of sea buckthorn raw material to ensure uniform initial quality characteristics and were subsequently processed using the two mechanical processing options combined with three drying methods, yielding six technological product variants in addition to the raw control. Each physicochemical parameter was measured in analytical replicates per sample: dry matter and water-soluble fraction in two replicates ($n = 2$), and vitamin C and total carotenoid contents in three replicates ($n = 3$), fraction yields (repeated weighings) were determined in three replicates ($n = 3$). The replicates are repeated analyses of the same product, not independent repetitions of the technological process. Results are expressed as mean ± standard deviation (SD). Statistical analysis was performed using Microsoft Excel 2021 (Microsoft Corporation, Redmond, WA, USA). One-way analysis of variance (ANOVA) was used to compare the sample variants, followed by Tukey's post hoc test to identify statistically significant differences between individual samples. Differences were considered statistically significant at $p < 0.05$. Statistical significance was assessed only for the physicochemical measurements. As each processing route was performed once, the resulting p-values describe differences among the analysed samples and not the reproducibility of the processes. Sensory data were not subjected to statistical analysis (Section 2.6).

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist with shortening and rephrasing parts of the text. The authors reviewed and edited all AI-assisted content and take full responsibility for the accuracy and integrity of the published work.

3. Results

The results of the study cover the effects of two mechanical processing options and three drying methods on the yield of processing fractions, physicochemical properties, and sensory quality of sea buckthorn-based tea products. Data are presented as mean values ± standard deviation, with statistical differences indicated for the physicochemical parameters; the sensory scores are presented descriptively.

3.1. Yield of Processing Fractions

The mechanical processing option clearly affected the yield of juice and pomace fractions obtained from sea buckthorn berries (Table 3). Slow screw pressing resulted in a high juice yield (91.75 ± 0.27%) and a low pomace fraction (8.25 ± 0.27%), indicating

efficient separation of the liquid fraction. In contrast, centrifugal pressing produced a markedly lower juice yield (65.33 ± 1.06%) and the highest pomace yield (34.67 ± 1.06%), suggesting that a considerable proportion of the berry mass remained in the by-product fraction. The pressing option therefore determined the distribution of berry mass between juice and pomace. Pomace yield was calculated by difference and therefore includes process losses (Section 2.2).

Table 3. Yield of juice and pomace fractions (repeated weightings) obtained by different mechanical processing methods (mean ± SD, $n = 3$).

Processing Option	Juice Yield (%)	Pomace Yield (%)
Option 1—slow screw pressing	91.75 ± 0.27	8.25 ± 0.27
Option 2—centrifugal pressing	65.33 ± 1.06	34.67 ± 1.06

3.2. Dry Matter Content

The dry matter content of all samples is summarized in Table 4.

Table 4. Dry matter content of sea buckthorn tea samples (mean ± SD, $n = 2$). Values followed by different superscript letters differ significantly ($p < 0.05$, Tukey's HSD test); letters were assigned in descending order of the mean (a = highest mean).

Sample Code	Dry Matter Content (%)
I—Control	21.79 ± 0.10 ^{d}
II—Tea cubes (Option 1)	92.50 ± 0.03 ^{a}
III—Tea cubes (Option 2)	92.65 ± 0.20 ^{a}
IV—Pomace strips (Option 1, IR)	89.02 ± 0.05 ^{c}
V—Pomace strips (Option 2, IR)	89.88 ± 0.09 ^{b}
VI—Pomace strips (Option 1, conv.)	89.03 ± 0.05 ^{c}
VII—Pomace strips (Option 2, conv.)	89.95 ± 0.06 ^{b}

Dry matter content varied among the sample variants depending on the raw material fraction and drying method (Table 4). The control sample (Code I) had a substantially lower dry matter content of 21.79 ± 0.10%, whereas all processed samples contained approximately 89–93% dry matter (residual moisture of 7.35–7.50% in the tea cubes and 10.05–10.98% in the pomace strips). The highest values were recorded for the freeze-dried tea cubes, with 92.65 ± 0.20% for Option 2 (Code III) and 92.50 ± 0.03% for Option 1 (Code II); both belonged to the same statistical group (a). Among the pomace strips, samples (Code V and VII) showed significantly higher dry matter contents (89.88 ± 0.09% for IR drying and 89.95 ± 0.06% for convection drying) than samples (Code IV and VI) (89.02 ± 0.05% and 89.03 ± 0.05%, respectively). The two replicate values for Code VI agreed closely (SD 0.05%, i.e., a difference of less than 0.1 percentage points between the replicates, comparable to the other samples), and their mean was practically identical to that of Code IV (89.02%), which was obtained from the same slow screw pomace dried by the other method; no replicate value was excluded, so the dry matter results for Code VI are not affected by any single mass value. Within each pressing option, infrared and convection drying resulted in pomace strips belonging to the same statistical group, i.e., no significant difference in dry matter content was found between the infrared- and convection-dried strips under the conditions applied. Overall, the tea cubes had the highest dry matter content, while the pomace strips showed slightly lower values, and the pressing option was associated with the small differences observed within the pomace-based products.

3.3. Vitamin C Content

Vitamin C content differed significantly among the processing and drying variants (Table 5). On an as-is basis, the unprocessed control showed the highest concentration (176.07 ± 3.42 mg/100 g, group a). The freeze-dried tea cubes contained considerably higher vitamin C levels than the pomace strips, with 104.35 ± 3.97 mg/100 g for Option 1 (Code II) and 96.12 ± 2.01 mg/100 g for Option 2 (Code III), corresponding to statistical groups b and c, respectively. In contrast, the pomace strips contained markedly lower vitamin C concentrations, ranging from 3.51 ± 0.00 to 6.45 ± 1.01 mg/100 g, and did not differ significantly from each other (group d). The titration volumes for the pomace strips were very low (≤0.3 mL); therefore, these values are close to the sensitivity limit of the titrimetric method and should be regarded as indicative.

Table 5. Vitamin C content of sea buckthorn tea samples on an as-is basis and on a dry-matter basis (mean ± SD, $n = 3$). Within a column, values followed by different superscript letters differ significantly ($p < 0.05$, Tukey's HSD test); letters were assigned in descending order of the mean (a = highest mean).

Sample Code	Vitamin C (mg/100 g, as-is)	Vitamin C (mg/100 g DM)
I—Control	176.07 ± 3.42 ^{a}	808.0 ± 15.7 ^{a}
II—Tea cubes (Option 1)	104.35 ± 3.97 ^{b}	112.8 ± 4.3 ^{b}
III—Tea cubes (Option 2)	96.12 ± 2.01 ^{c}	103.7 ± 2.2 ^{b}
IV—Pomace strips (Option 1, IR)	3.51 ± 0.00 ^{d}	3.95 ± 0.00 ^{c}
V—Pomace strips (Option 2, IR)	5.25 ± 1.75 ^{d}	5.85 ± 1.95 ^{c}
VI—Pomace strips (Option 1, conv.)	3.51 ± 0.00 ^{d}	3.94 ± 0.00 ^{c}
VII—Pomace strips (Option 2, conv.)	6.45 ± 1.01 ^{d}	7.17 ± 1.13 ^{c}

Values on a dry-matter basis (DM) were calculated for each replicate using the mean dry matter content of the sample (Equation (5)) and were compared by Tukey's HSD test (letters are given separately for each column).

On a dry-matter basis, the vitamin C content of the control was 808.0 ± 15.7 mg/100 g DM (group a), that of the tea cubes 112.8 ± 4.3 mg/100 g DM (Code II) and 103.7 ± 2.2 mg/100 g DM (Code III), which did not differ significantly from each other (group b) and corresponded to approximately 13–14% of the control value, and that of the pomace strips 3.94–7.17 mg/100 g DM (group c; 0.5–0.9% of the control). Thus, the higher as-is concentration of the control reflects its much higher vitamin C level per unit of dry matter, despite its lower dry matter content, and the large differences between the control and the processed products are not an effect of water removal. These values describe the concentration in each product and do not represent retention in the whole berry mass, because vitamin C was distributed between the juice and pomace fractions during pressing and no mass balance was determined. Overall, the tea cubes contained considerably more vitamin C than the pomace strips, although both processing options resulted in lower vitamin C concentrations than the raw control.

3.4. Total Carotenoid Content

Total carotenoid content was significantly affected by the applied processing and drying methods ($p < 0.05$) (Table 6). On an as-is basis, the control sample had the lowest carotenoid content (5.41 ± 0.01 mg/100 g, group d), whereas all processed samples showed significantly higher values. The tea cubes contained 13.09 ± 0.01 mg/100 g (Code II), corresponding to statistical group b, and 13.20 ± 0.00 mg/100 g (Code III), which was statistically intermediate between groups a and b. The highest carotenoid content was observed in pomace strips obtained using Option 2, reaching 13.38 ± 0.00 mg/100 g under both infrared (Code V) and convection drying (Code VII), with both samples belonging to group a. In contrast, pomace strips obtained using Option 1 contained significantly lower carotenoid

levels, at 7.75 ± 0.04 mg/100 g after infrared drying (Code IV) and 7.56 ± 0.25 mg/100 g after convection drying (Code VI), although both remained higher than the control on an as-is basis.

Table 6. Total carotenoid content of sea buckthorn tea samples on an as-is basis and on a dry-matter basis (mean ± SD, $n = 3$). Within a column, values followed by different superscript letters differ significantly ($p < 0.05$, Tukey's HSD test); letters were assigned in descending order of the mean (a = highest mean).

Sample Code	Total Carotenoids (mg/100 g, as-is)	Total Carotenoids (mg/100 g DM)
I—Control	5.41 ± 0.01 ^{d}	24.83 ± 0.06 ^{a}
II—Tea cubes (Option 1)	13.09 ± 0.01 ^{b}	14.15 ± 0.01 ^{c}
III—Tea cubes (Option 2)	13.20 ± 0.00 ^{ab}	14.25 ± 0.00 ^{c}
IV—Pomace strips (Option 1, IR)	7.75 ± 0.04 ^{c}	8.70 ± 0.04 ^{d}
V—Pomace strips (Option 2, IR)	13.38 ± 0.00 ^{a}	14.89 ± 0.00 ^{b}
VI—Pomace strips (Option 1, conv.)	7.56 ± 0.25 ^{c}	8.49 ± 0.28 ^{d}
VII—Pomace strips (Option 2, conv.)	13.38 ± 0.00 ^{a}	14.87 ± 0.00 ^{b}

Values on a dry-matter basis (DM) were calculated for each replicate using the mean dry matter content of the sample (Equation (5)) and were compared by Tukey's HSD test (letters are given separately for each column).

The higher as-is carotenoid concentrations of the processed samples are largely attributable to the removal of water (dry matter increased from 21.79% to 89–93%). On a dry-matter basis, the control contained 24.83 ± 0.06 mg/100 g DM (group a), whereas all processed products had significantly lower values: 14.89 ± 0.00 and 14.87 ± 0.00 mg/100 g DM in the Option 2 pomace strips (Codes V and VII; group b; approximately 60% of the control), 14.15 ± 0.01 and 14.25 ± 0.00 mg/100 g DM in the tea cubes (Codes II and III; group c; approximately 57%), and 8.70 ± 0.04 and 8.49 ± 0.28 mg/100 g DM in the Option 1 pomace strips (Codes IV and VI; group d; approximately 34–35%). Infrared and convection drying did not differ within either pressing option, whereas the pressing option was associated with differences within the pomace strips.

3.5. Water-Soluble Fraction of the Tea Samples

The water-soluble fraction of the dry matter of the tea samples in water at 60 ± 1 °C differed depending on the processing and drying method (Table 7).

Table 7. Water-soluble fraction of the dry matter of sea buckthorn tea samples in water at 60 ± 1 °C (mean ± SD, $n = 2$). Values followed by different superscript letters differ significantly ($p < 0.05$, Tukey's HSD test); letters were assigned in descending order of the mean (a = highest mean) Both columns are expressed as a percentage of the dry matter mass of the sample taken for the infusion (Equations (6) and (7)); the water-soluble fraction was calculated by difference.

Sample Code	Insoluble Residue (% DM)	Water-Soluble Fraction (% DM)
II—Tea cubes (Option 1)	7.56 ± 0.03 ^{c}	92.44 ± 0.03 ^{b}
III—Tea cubes (Option 2)	7.35 ± 0.04 ^{d}	92.65 ± 0.04 ^{a}
IV—Pomace strips (Option 1, IR)	89.02 ± 0.03 ^{b}	10.98 ± 0.03 ^{c}
V—Pomace strips (Option 2, IR)	89.88 ± 0.06 ^{a}	10.12 ± 0.06 ^{d}
VI—Pomace strips (Option 1, conv.)	89.02 ± 0.04 ^{b}	10.98 ± 0.04 ^{c}
VII—Pomace strips (Option 2, conv.)	89.96 ± 0.06 ^{a}	10.04 ± 0.06 ^{d}

The water-soluble fraction of the dry matter of the tea samples in water at 60 ± 1 °C (5 g per 100 mL, 5 min) differed significantly depending on the product type and the processing option (Table 7). The water-soluble fraction was by far the highest in the tea

cubes, with 92.65 ± 0.04% for Option 2 (Code III) and 92.44 ± 0.03% for Option 1 (Code II), corresponding to insoluble residues of only 7.35 and 7.56% (Supplementary Figure S6). Although the difference between the two tea cubes was small (0.21 percentage points), it was statistically significant ($p < 0.05$). In contrast, only 10.04–10.98% of the dry matter of the pomace strips was extracted into water, with insoluble residues of 89.02–89.96%, and the strips remained visibly intact in water (Supplementary Figure S7). Among the pomace strips, Option 1 strips (Codes IV and VI) had a slightly but significantly higher water-soluble fraction (10.98 ± 0.03 and 10.98 ± 0.04%) than Option 2 strips (Codes V and VII; 10.12 ± 0.06 and 10.04 ± 0.06%), whereas infrared and convection drying did not differ within either pressing option (same letters). The largest difference in water-soluble fraction was thus between the two product formats (cubes vs. strips), which differ in both fraction and drying method; within the pomace strips, the pressing option was associated with a small difference, and no significant difference was found between the infrared and convection regimes tested. The infusion time of 5 min was the same for all samples, and whether equilibrium was reached was not verified (Section 4.9).

3.6. Sensory Evaluation

The sensory profile of the sea buckthorn tea products, expressed as mean scores of 30 assessors (1–5 point scale, where 1 = very bad and 5 = very good) for taste, mouthfeel, color and aroma, is presented in Figure 2. Only the mean scores were recorded; the results are therefore described descriptively, without statistical comparison. The soluble solids of the infusions were not standardized and individual scores were unavailable; the scores are therefore indicative of liking under the infusion conditions applied.

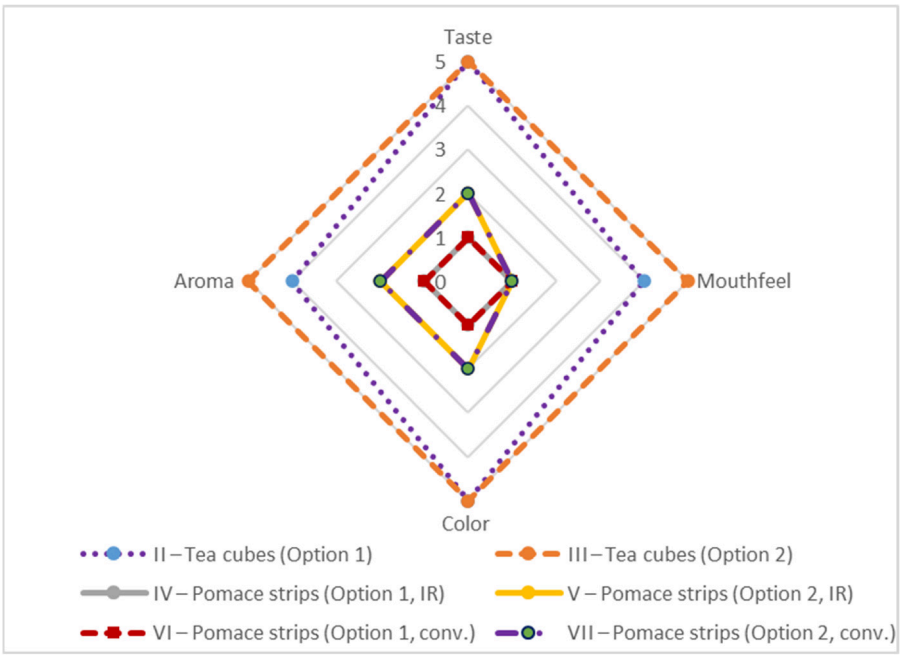

Figure 2. Sensory evaluation of sea buckthorn tea samples variants.

The pomace strips received the lowest scores (1–2 points for all attributes), regardless of whether infrared or convection drying was applied; mouthfeel was scored 1 for all pomace strips. The strips obtained by centrifugal pressing (Codes V and VII) scored 2 points for taste, color and aroma, whereas those obtained by slow screw pressing (Codes IV and VI) scored 1 point. In contrast, the freeze-dried tea cubes received consistently high scores of 4–5 points. Code III received the maximum score of 5 for all attributes, and Code II scored 5

for taste and color and 4 for mouthfeel and aroma. Thus, the freeze-dried tea cubes showed the most favorable sensory profile among the evaluated products, and the pomace strips the least favorable, especially in terms of mouthfeel.

4. Discussion

4.1. Effect of Mechanical Processing on Juice and Pomace Yield

The two mechanical processing options produced markedly different partitioning of the raw material into juice and pomace, and this partitioning determined the two product formats developed in the present study (tea cubes and pomace strips). Slow screw pressing (Option 1) yielded the largest juice fraction (91.75 ± 0.27%) and the smallest solid residue (8.25 ± 0.27%), whereas centrifugal pressing (Option 2) yielded substantially less juice (65.33 ± 1.06%) and generated a larger pomace fraction (34.67 ± 1.06%). The difference in juice yield between the two methods was 26.42 percentage points, showing that, under the conditions investigated, the two options distributed the raw material very differently between the liquid and solid fractions. Because each option was performed once and with a different machine (Section 2.2), this difference reflects the combined effect of the pressing principle and of the specific equipment and cannot be attributed to the pressing principle alone.

These differences may be associated with the distinct mechanical principles of the two extraction methods. In the twin-gear slow juicer (Option 1), the berries are crushed and squeezed between two slowly rotating gears, so that juice is released mainly through pressure-induced rupture of the cells under continuous compression and shearing and a comparatively long residence time [27,28]. The efficiency of juice extraction also depends on factors such as screw geometry, operating speed, applied pressure, residence time, and the mechanical properties of the plant matrix. Kassenov et al. [22] demonstrated that juice yield from sea buckthorn berries processed using an instrumented screw press was sensitive to the pressing conditions, including spring force, screw speed, and the resulting internal pressure. Their findings support the importance of equipment design and operating parameters when interpreting juice extraction efficiency. However, differences between the yields reported in their study and those obtained in the present work should be interpreted cautiously because the equipment configurations, processing conditions, and experimental procedures may differ.

A higher juice yield of slow (cold-press) juicers than of centrifugal juicers has also been reported for other fruits, for example pineapple (92% vs. 47%) [27], although the effects of the juicer type on juice composition are not consistent across studies. In contrast, in the centrifugal juicer (Option 2) the berries are rapidly disintegrated by a high-speed rotating grating blade (mechanical shearing of the cells), and the juice is separated from the pulp through a sieve basket by centrifugal force, with a very short contact time and without sustained compression of the pulp [27,28].

The efficiency of this process may depend on the structure and mechanical properties of the plant tissue, the ease with which liquid is released, and the amount of liquid retained within the residual solids. The higher pomace yield obtained with centrifugal pressing (34.67 ± 1.06%), compared with slow screw pressing (8.25 ± 0.27%), indicates that a greater proportion of the initial material remained in the solid fraction after centrifugal processing. This difference may reflect variations in the extent of tissue disruption and liquid–solid separation achieved by the two methods. Nevertheless, because tissue disruption, residual pomace moisture, and the amount of liquid retained in the solids were not directly measured, these mechanisms should be considered plausible explanations rather than experimentally confirmed causes of the observed yield differences. In addition, pomace yield was calculated by difference and therefore includes process losses (e.g., material retained on the gears,

blade, sieve and other machine surfaces), which may differ between the two machines. The values also refer to wet pomace, i.e., they include the liquid retained in the residue, and do not represent the mass of pomace solids.

4.2. Drying Conditions and Moisture Removal

The products were obtained by two principally different ways of moisture removal. In freeze-drying (tea cubes), water is removed by sublimation of ice from the frozen juice under reduced pressure (12 Pa); the driving force is the water-vapour pressure gradient between the ice front and the condenser, and the solid matrix remains largely in the form of a porous structure [24]. In infrared and convection drying (pomace strips), moisture removal is driven by the temperature and water-vapour gradients between the material and the surrounding air and is limited by the internal resistance to moisture transport. This resistance increases with the layer thickness (5 mm in this study) and the compactness of the pomace layer. In addition, the surface of sea buckthorn berries is covered with a dense wax layer that has been reported to restrict moisture transfer during drying [29], and the skin is a component of the pomace. Infrared radiation is absorbed mainly by the surface layers of the material rather than penetrating it, and the heat is subsequently conducted inwards; infrared heating therefore does not by itself remove the internal resistance to moisture transport.

Together with the low drying temperatures (45 and 50 °C) selected to limit the degradation of vitamin C and carotenoids, these factors probably contributed to the long duration of pomace drying (24–28 h). This is considerably longer than the 250 min reported as the shortest drying time for sea buckthorn pomace in a study that compared several drying techniques under different conditions [23]. The prolonged exposure of the pomace to heat and oxygen is relevant for the interpretation of the vitamin C and carotenoid results (Sections 4.4 and 4.5).

The comparison between infrared and convection drying has to be interpreted with caution. The two regimes differed not only in the mode of heat transfer but also in the drying temperature (45 ± 1 °C vs. 50 ± 1 °C) and the air velocity (1.5 vs. 0.3 m/s) (Section 2.3.2). Consequently, the absence of significant differences between the two regimes in the properties of the pomace strips (Sections 4.3–4.7) means that, under the specific conditions applied, they led to similar products; it does not demonstrate that the heating mechanism itself is irrelevant. Moreover, both pomace regimes were stopped by the same end-point criterion (mass change < 0.1 g per hour), whereas freeze-drying was carried out for a fixed time of 48 h, and drying kinetics were not recorded. Therefore, conclusions on drying efficiency cannot be drawn, and only the final properties of the products are compared.

4.3. Dry Matter Content

The dry matter content of the fresh control sample (21.79 ± 0.10%) corresponds to a moisture content of approximately 78%. This value lies within the range reported for fresh sea buckthorn berries (approximately 70–85% moisture) [29] and is slightly lower than the 81.91 ± 0.86% (wet basis) reported by Tan et al. [29] for thawed berries, which may be related to differences in cultivar, ripeness and geographical origin [4]. All processed products contained 89.0–92.7% dry matter, i.e., a residual moisture of 7.35–7.50% in the tea cubes and 10.05–10.98% in the pomace strips (Table 4); the latter was close to the nominal 10% end-point of pomace drying (Section 2.3.2). Residual moisture of this magnitude is typical of dried plant products; however, dry matter alone is not a sufficient indicator of microbiological and physicochemical stability, because stability depends on water activity, packaging and storage conditions [30]. Water activity was not measured in this study. The freeze-dried tea cubes (Codes II and III; 92.50–92.65%) reached significantly higher

dry matter content than the pomace strips (89.02–89.95%). This difference may be related to the different mechanism of moisture removal and to the different end-point of drying (Section 4.2). At the same time, the two formats differ simultaneously in the fraction and in the drying method, and in composition and structure, so the contribution of each factor cannot be separated (Section 4.8). Among the pomace strips, drying method (infrared vs. convection) had no significant effect on dry matter content within either processing option (Codes IV vs. VI; Codes V vs. VII; Table 4), suggesting that, under the conditions applied, the two regimes removed a comparable amount of moisture. The pomace strips obtained by slow screw pressing (Codes IV and VI; 89.02–89.03%) had slightly but significantly lower dry matter content than those obtained by centrifugal pressing (Codes V and VII; 89.88–89.95%). The difference is smaller than one percentage point and of limited practical significance. It should also be noted that statistical significance refers to analytical replicates of a single drying run (Section 2.8).

4.4. Vitamin C Content

On an as-is basis, vitamin C content decreased from the fresh control (176.07 ± 3.42 mg/100 g) through the freeze-dried tea cubes (96.12–104.35 mg/100 g, Codes II–III) to the infrared- or convection-dried pomace strips (3.51–6.45 mg/100 g, Codes IV–VII). Expressed on a dry-matter basis, the difference between the control (808.0 ± 15.7 mg/100 g DM) and the processed products is even more evident: the tea cubes contained 103.7–112.8 mg/100 g DM (approximately 13–14% of the control) and the pomace strips 3.94–7.17 mg/100 g DM (0.5–0.9%) (Table 5). The lower vitamin C contents of the processed products are therefore not an effect of water removal but reflect a lower concentration of vitamin C in the solids.

These values describe the concentration of vitamin C in each final product and not its retention during processing. Vitamin C is water-soluble and is expected to be distributed mainly with the aqueous phase during pressing, whereas the pomace retains only the residual liquid. The very low vitamin C content of the pomace strips is therefore the result of several factors acting together: (i) partitioning between the fractions during pressing, (ii) heat and oxygen exposure during prolonged drying (24–28 h), and (iii) the limited sensitivity of the titrimetric method at such low levels (titration volumes ≤ 0.3 mL). Their relative contributions cannot be separated, because no mass balance was determined and the fraction and the drying method are confounded.

This trend reflects the well-documented thermal and oxidative lability of ascorbic acid, which degrades primarily through oxidation to dehydroascorbic acid, a reaction accelerated by heat, oxygen exposure and prolonged processing time [26]. For sea buckthorn berries, vacuum freeze-drying and pulsed-vacuum drying preserved more ascorbic acid than hot-air, infrared and infrared-assisted hot-air drying [24], and in sea buckthorn pomace the highest vitamin C content was found after pulsed-vacuum drying [23]; the dependence of bioactive compounds on the drying technique in sea buckthorn berries has also been shown by Li et al. [25]. The direction of the difference between the freeze-dried and heat-dried products observed here is therefore in line with the literature. However, the freeze-dried tea cubes contained only 13–14% of the dry-matter-based vitamin C content of the control, which is a considerable decrease for a low-temperature process. Freeze-drying alone thus cannot explain the observed values, and other stages probably contributed: thawing for 12–14 h, exposure of the disintegrated berry tissue to oxygen and oxidative enzymes during pressing (possibly more pronounced in the high-speed centrifugal juicer), freezing, and storage of the dried products for 7 days at about 22 °C before analysis. Because vitamin C was not determined in the fresh juice or immediately after drying, the contribution of each stage cannot be quantified. In addition, titration with Tillmans' reagent is not specific for

ascorbic acid, since other reducing compounds may also reduce the dye and the end-point in coloured extracts may be difficult to detect.

The tea cubes from slow screw pressing contained slightly more vitamin C on an as-is basis than those from centrifugal pressing (104.35 vs. 96.12 mg/100 g, $p < 0.05$), but the difference was not significant on a dry-matter basis (112.8 vs. 103.7 mg/100 g DM). A contribution of greater air incorporation in the high-speed juicer is conceivable but was not verified, and the literature on the effect of the juicer type on the vitamin content of juices is inconsistent [27,28]. Among the pomace strips, vitamin C content did not differ significantly between processing options or drying methods (Codes IV–VII; Table 5). Since these values are close to the sensitivity limit of the method, the absence of differences should be regarded as indicative and does not prove that the two drying regimes act identically on vitamin C. Despite the marked decrease, all dried products contained measurable amounts of vitamin C; however, a portion of 5 g of tea cubes supplies only about 4.8–5.2 mg of vitamin C (assuming complete dissolution), and the corresponding amount from pomace strips is below 0.4 mg, so their contribution to vitamin C intake is modest.

4.5. Total Carotenoid Content

On an as-is basis, all processed products contained more carotenoids (7.56–13.38 mg/100 g) than the fresh control (5.41 ± 0.01 mg/100 g), with the highest values in the tea cubes and in the Option 2 pomace strips (13.09–13.38 mg/100 g; Table 6). This 2.4–2.5-fold increase is, however, largely a consequence of water removal, since dry matter increased approximately 4.1–4.3-fold (from 21.79% to 89–93%). When expressed on a dry-matter basis, all processed products contained less carotenoids than the control (24.83 ± 0.06 mg/100 g DM): approximately 60% in the Option 2 pomace strips (14.87–14.89 mg/100 g DM), 57% in the tea cubes (14.15–14.25 mg/100 g DM) and 34–35% in the Option 1 pomace strips (8.49–8.70 mg/100 g DM).

The carotenoid concentration of the pomace strips depended on the pressing option but not on the drying method: on a dry-matter basis, the Option 2 strips (Codes V and VII) contained about 1.7 times more carotenoids than the Option 1 strips (Codes IV and VI), irrespective of infrared or convection drying (Table 6). The tea cubes from the two pressing options did not differ in carotenoid content on a dry-matter basis (14.15 vs. 14.25 mg/100 g DM), although their juice yields differed by 26 percentage points.

The markedly lower carotenoid content of the pomace strips obtained by slow screw pressing (Codes IV and VI) relative to those obtained by centrifugal pressing (Codes V and VII) is consistent with the differences in fraction yield reported in Section 4.1. Centrifugal pressing produced a substantially larger pomace fraction (34.67%) than slow screw pressing (8.25%), which may mean that a greater proportion of the berry skin and pulp, the tissues in which carotenoids are predominantly located, remained in the solid residue, whereas slow screw pressing, which extracted juice more completely, left a smaller and more juice-depleted residue. This explanation is hypothetical: the distribution of carotenoids between the fractions was not determined, and the transfer of the carotenoid-rich pulp oil [5] into the juice (as cloud or oil droplets) may differ between the two machines. This finding indicates that the pressing option, rather than the subsequent drying method, was associated with the carotenoid content of the pomace-based products.

According to González-Peña et al. [31], carotenoids are intrinsically more heat-stable than ascorbic acid because of their lipophilic character, which limits their exposure to aqueous-phase oxidative pathways; at the same time, they are susceptible to oxidation and isomerization under the influence of oxygen, light and heat [31]. In kiwifruit, carotenoid contents also decreased after all drying methods, with smaller losses after freeze- and vacuum-drying than after prolonged convective and natural drying [32]. The lower dry-

matter-based contents of all processed products relative to the control (34–60%) show that a substantial loss, or a change in extractability, occurred during pressing, drying and storage. Because carotenoids were not determined in the fresh juice and wet pomace or immediately after drying, losses during pressing, drying (24–28 h) and 7-day storage cannot be distinguished; the porous structure of freeze-dried products may additionally facilitate oxygen access.

The method used should also be taken into account. Total carotenoids were determined spectrophotometrically at a single wavelength (470 nm) and expressed as carotene equivalents [33]; this approach does not distinguish individual carotenoids, may be affected by other pigments absorbing in this region, and the extraction efficiency from matrices of different composition (fresh berries, juice solids rich in sugars and organic acids, pomace) was not verified. The values should therefore be regarded as comparative indices.

4.6. Water-Soluble Fraction of the Components Contained in the Tea Samples

The two product formats behave fundamentally differently in water. The freeze-dried tea cubes consist of dried juice solids and dissolve on rehydration, whereas for the pomace strips soluble compounds must be extracted from a solid, fibre-rich matrix. These are different mass-transfer processes with different resistances: the dissolution of the porous freeze-dried juice matrix is rapid, while extraction from pomace depends on the diffusion of soluble compounds through the cell walls and the waxy skin [29] of strips with a thickness of several millimetres, and is limited by contact time and particle size. The water-soluble fraction is used here as a common descriptor, but it describes dissolution in one case and extraction in the other.

The water-soluble fraction, expressed as the proportion of the dry matter of the dried product that passed into the infusion at 60 ± 1 °C, was 92.44–92.65% for the freeze-dried tea cubes (Codes II and III) and only 10.04–10.98% for the pomace strips (Table 7), which remained visibly undissolved (Figure S7). The very low water-soluble fraction of the pomace strips is consistent with their composition (a fibre-rich residue that is predominantly insoluble) and with the fact that they were infused as whole strips without particle-size reduction. Moreover, a 5-min infusion with water of 60 °C initial temperature (52 ± 1 °C at the end of infusion) is short, and it was not verified whether extraction equilibrium was reached. The values for the pomace strips therefore reflect the extraction under these conditions rather than the maximum amount of extractable compounds, and longer extraction times, higher temperatures or smaller particle sizes might increase the extracted fraction.

Among the pomace strips, the strips from slow screw pressing (Codes IV and VI; 10.98%) had a slightly but significantly higher water-soluble fraction than those from centrifugal pressing (Codes V and VII; 10.04–10.12%), whereas infrared and convection drying did not differ within either pressing option. The difference between the pressing options (about 0.9 percentage points) is small compared with the difference between the product formats and is of limited practical significance, and its cause was not investigated. It should be noted that the differences in water-soluble fraction among the pomace strips are of the same magnitude as the differences in their residual moisture (Table 4), and that the water-soluble fraction was determined gravimetrically in a single infusion; the values should therefore be considered as relative indices of the water-soluble fraction under the specified conditions.

A reduction in particle size and disruption of the cell-wall matrix increases the extractability of cell-bound compounds from plant by-products, as shown for high-pressure homogenization of tomato processing by-products [34], and tea-industry residues (black tea waste fibres) have been converted into instant tea-type products after additional processing [35]. These findings suggest that milling or other particle-size reductions in the

pomace could improve the transfer of soluble compounds into the infusion; however, this was not tested in the present study.

4.7. Sensory Quality

The sensory results are descriptive (mean scores of 30 untrained assessors; Section 3.6, Figure 2), and no statistical comparison was possible; differences between samples are therefore discussed as observed trends only. The tea cubes (Codes II and III) were rated highest (4–5 points), while the pomace strips (Codes IV–VII) received markedly lower scores (1–2 points for all attributes, i.e., "very bad" to "bad" on the scale used). This hierarchy is consistent with the water-soluble fraction results (Section 4.6): the infusions of the tea cubes contained the dissolved juice solids, whereas the infusions of the pomace strips contained little extract and visible particles (Figure S7), and mouthfeel, defined as the perceived body of the liquid and the presence of particles, was scored 1 for all pomace strips. The identical product-to-water ratio (5 g/100 mL) applied to all products delivers different amounts of soluble solids from products of different composition, which also affects the sensory evaluation; part of the sensory differences may therefore reflect differences in the extract content of the infusions rather than product quality alone.

A small sensory difference was observed between the two tea cubes: Code III, produced from juice obtained by centrifugal pressing, scored 5 for all attributes, whereas Code II, from slow screw pressing, scored 4 for mouthfeel and aroma, despite both samples showing comparable dry matter, vitamin C (dry-matter basis) and water-soluble fraction values. As the difference is one point in two attributes and no information on variability is available, it should not be over-interpreted. If real, it might be associated with differences in the composition of the two juices (e.g., fine pulp, oil droplets or volatile compounds), which depend on the pressing technique; however, the lipid and volatile composition of the juices was not determined, and this remains a hypothesis (Section 4.9).

Within the pomace strips, the strips from centrifugal pressing (Codes V and VII) scored 2 points for taste, color and aroma and those from slow screw pressing (Codes IV and VI) 1 point, with no difference between infrared and convection drying. The pomace strips were rated "bad" in the infusion format tested. Because the soluble solids of the infusions were not standardized and individual scores were unavailable, this indicates low liking under these specific conditions rather than a definitive judgement of product acceptability; further processing (such as milling or blending) or reformulation would be needed to improve their sensory performance. The panel evaluated liking only; no descriptive sensory profile was obtained, so the sensory attributes cannot be linked to specific compounds.

4.8. Comparative Assessment of Processing Routes and Practical Implications

Because the juice was only freeze-dried and the pomace was only dried by infrared or convection, the fraction and the drying method are completely confounded in the comparison between tea cubes and pomace strips. The higher dry matter content, vitamin C content, water-soluble fraction and sensory scores of the tea cubes cannot therefore be assigned to either factor; in particular, it cannot be excluded that freeze-dried pomace would behave differently from the infrared- or convection-dried pomace. Reliable conclusions concern only (i) the effect of the pressing option within each product format and (ii) the comparison of infrared and convection drying within the pomace strips.

Within the tea cubes, the two pressing options gave similar products: dry matter (92.50 vs. 92.65%), vitamin C on a dry-matter basis and carotenoids on a dry-matter basis (14.15 vs. 14.25 mg/100 g DM) did not differ significantly. Only small differences were found in vitamin C on an as-is basis (104.35 vs. 96.12 mg/100 g, higher for Option 1), in water-soluble fraction (92.44 vs. 92.65%, higher for Option 2) and in sensory scores (mouthfeel and aroma

5 vs. 4 points, higher for Option 2). In the pomace strips, the pressing option was associated with a large difference in carotenoid content (14.87–14.89 vs. 8.49–8.70 mg/100 g DM, higher for Option 2), small differences in dry matter (89.88–89.95 vs. 89.02–89.03%, higher for Option 2) and water-soluble fraction (10.04–10.12 vs. 10.98%, higher for Option 1), and a one-point difference in sensory scores (2 vs. 1 point for taste, color and aroma, higher for Option 2), whereas vitamin C did not differ. Infrared and convection drying did not differ in any of the parameters of the pomace strips, and their sensory scores were identical. Statistical differences refer to analytical replicates of a single processing run (Section 2.8), and the sensory scores are descriptive. The main effect of the pressing option is thus the partitioning of the berry mass between juice and pomace (Section 4.1), which determines the amount of material available for each product format.

The freeze-dried juice tea cubes showed the highest dry matter content, vitamin C content, water-soluble fraction and sensory scores among the products studied (as fraction and drying method are confounded, this cannot be attributed to freeze-drying itself), while the carotenoid content on a dry-matter basis was comparable to, or slightly lower than, that of the Option 2 pomace strips. At the same time, freeze-drying is generally more costly than hot-air or infrared drying [24] and required 48 h in this study. The pomace strips valorize a by-product, but in their present format only about 10% of their dry matter is extracted into water; they are low in vitamin C and received low liking scores (1–2 out of 5) under the infusion conditions applied and are, in their present format, not suitable as a standalone tea raw material. Among them, the Option 2 pomace (larger yield, higher carotenoid content on a dry-matter basis, slightly higher sensory scores, water-soluble fraction lower by about 0.9 percentage points) appears to be the more promising raw material for further development; this, however, requires further processing (e.g., milling, blending, formulation), and lipophilic carotenoids and fibre, which are among the reasons for pomace valorization, are not transferred into an aqueous infusion to a large extent. The use of milled pomace as an ingredient consumed together with the infusion could therefore be considered.

Translating this feasibility into a commercially viable product line will additionally require addressing the practical challenges documented more broadly for upcycled food categories, including non-homogeneous raw-material supply, the need for standardized processing conditions, and the current absence of a unified certification and labelling framework for upcycled ingredients, which have recently been identified as key barriers to the large-scale commercialization of food products derived from processing by-products and residues [36]. These considerations define the scope of the additional process-standardization and regulatory work that would be required before the sea buckthorn products developed in this study could progress from a laboratory-scale technology to a commercial product.

4.9. Study Scope and Directions for Future Research

The interpretation of the results is subject to the following limitations. All technological variants were derived from a single batch of raw material, and pressing and drying were performed once for each processing route; the replicates are repeated analyses of the same product and not independent repetitions of the technology (Section 2.8). Statistical differences therefore describe the analysed products and not the reproducibility of the processes, and the results cannot be generalized to other batches, harvest seasons, cultivars or equipment; the effect of the pressing option is also inseparable from the machine used. Extending the present comparisons across multiple raw-material batches and harvest seasons is planned as a next step, given the known variability of sea buckthorn composition with genotype, geographical origin, and cultivation conditions [4]. Fraction and drying method are confounded (Section 4.8), and the infrared and convection regimes differed in

temperature and air velocity (Section 4.2); future studies should apply all drying methods to both fractions (including freeze-dried pomace) and record drying kinetics.

Applied pressure, sieve aperture and product temperature during pressing were not measured, and no mass balance was determined: dry matter, vitamin C and carotenoids were not analysed in the fresh juice and wet pomace, and vitamin C and carotenoids were not measured immediately after drying, so the effects of pressing, drying and 7-day storage cannot be separated. The lipid fraction of the sea buckthorn pulp [5] may influence freeze-drying, the appearance of the infusion (oil layer) and storage stability (oxidative rancidity); fat content, lipid oxidation, antioxidant capacity, total phenolic content and microstructure were not assessed, and the statements on lipid partitioning in this Discussion are hypotheses. Future studies will extend the characterization to these parameters. Water activity was not measured; although the dry matter values obtained (≥89%) are typical of dried plant products, a direct water activity measurement combined with an accelerated or real-time storage trial is planned in subsequent work to allow a more rigorous assessment of shelf-life stability [30].

Analytical limitations include the low sensitivity of the titrimetric vitamin C determination for the pomace strips, the single-wavelength determination of total carotenoids as carotene equivalents, and a single infusion time (5 min) without verification of extraction equilibrium. The same product-to-water ratio (5 g/100 mL) was applied to products of different composition, which affects both the water-soluble fraction and the sensory results. The extract content (soluble solids) of the infusions, which represent the final consumed product, was not determined. In the sensory evaluation, only the mean scores of 30 untrained consumers were recorded, without variability data or statistical analysis. A larger and more demographically varied consumer panel, with recorded individual scores and a formal preference ranking, would allow the present acceptability differences to be validated with greater statistical power. Extraction kinetics at different times, temperatures and particle sizes of the pomace, and the performance of the products under real storage conditions, will be addressed in further work to fully establish the potential of the sea buckthorn tea-type products developed here. Future studies should determine the extract content directly in the infusions and adjust the dried-material-to-water ratio so that the mass of soluble components per volume of water is constant across samples, and the sensory evaluation should then be repeated under these standardized conditions.

5. Conclusions

This study demonstrated that sea buckthorn (*Hippophae rhamnoides* L.) juice and juice-pressing pomace can be processed into tea-type products by combining mechanical pressing and drying; however, only the freeze-dried juice (tea cubes) reached high physicochemical and sensory quality, whereas the pomace strips in their current format did not. The choice of the mechanical processing option (slow screw pressing or centrifugal pressing) was the primary determinant of juice and pomace fraction yield (91.75% vs. 65.33% juice) and directed the raw material toward either a juice-based (tea cube) or a pomace-based (strip) product route, although this effect cannot be separated from the machine used. Under the specific conditions tested (45 °C and 1.5 m/s vs. 50 °C and 0.3 m/s), infrared and convection drying did not differ significantly in the physicochemical parameters measured for the pomace strips, and, because juice was only freeze-dried and pomace only infrared- or convection-dried, the effects of fraction and drying method cannot be separated.

Freeze-dried tea cubes obtained from pressed juice achieved the highest dry matter content (92.50–92.65%), vitamin C content (96.12–104.35 mg/100 g), water-soluble fraction (92.44–92.65% of dry matter) and sensory liking scores (4–5 points) among all product variants, while their carotenoid content on a dry-matter basis (14.15–14.25 mg/100 g DM)

was comparable to that of the pomace strips from centrifugal pressing and lower than in the raw berries. This identifies the freeze-dried juice product as the most promising of the tested product formats when product quality is the priority, although the contribution of freeze-drying cannot be separated from that of the raw material, although freeze-drying is generally more costly. Among the pomace-based strip products, those derived from centrifugal pressing had higher carotenoid content (about 1.7 times on a dry-matter basis) and slightly higher descriptive sensory scores (2 vs. 1 point) than those from slow screw pressing, whereas the water-soluble fraction was slightly higher in the slow screw strips (10.98 vs. 10.04–10.12%), a difference of limited practical significance. Centrifugal pomace, with its larger yield, therefore, appears to be the more promising raw material for further development. However, only about 10% of the dry matter of all pomace strips was extracted into water; they were low in vitamin C and received low liking scores (1–2 points), and would require additional processing, such as milling, blending or reformulation, before application in a tea-type product.

Overall, these findings show that sea buckthorn juice can be transformed into a tea-type product of high physicochemical quality and high liking scores, whereas the valorization of pomace in the strip format remains a challenge. They provide practical guidance for selecting mechanical processing and drying combinations according to the intended product format. As the results are based on a single raw-material batch, analytical replicates and descriptive sensory data, they should be confirmed across several batches and extended to freeze-dried and milled pomace. The sensory conclusions are descriptive and indicative, because the soluble solids of the infusions were not standardized and individual scores were unavailable; statistical statements apply to the physicochemical measurements of the analysed samples only. Further studies assessing antioxidant capacity, total phenolic content, water activity and shelf-life stability are needed to fully characterize the nutritional value and commercial potential of the developed products.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture16222549/s1. Figure S1: Pomace pulp before drying, obtained by slow screw pressing (Option 1) and centrifugal pressing (Option 2); Figure S2: Juice obtained by slow screw pressing (Code II) and centrifugal pressing (Code III), poured into silicone molds and frozen; Figure S3: Freeze-dried tea cubes obtained from juice by slow screw pressing (Code II) and centrifugal pressing (Code III); Figure S4: Pomace strips produced via infrared drying (Code IV, Option 1; Code V, Option 2); Figure S5: Pomace strips produced via convection hot-air drying (Code VI, Option 1; Code VII, Option 2); Figure S6: Freeze-dried tea cubes (Codes II and III) in water at 60 ± 1 °C after 5 min and stirring; Figure S7: Dried pomace strips (Codes IV–VII) in water at 60 ± 1 °C.

Author Contributions: Conceptualization, Ž.J.; methodology, Ž.J.; formal analysis, V.S.; investigation, Ž.J.; resources, Ž.J.; data curation, Ž.J.; writing—original draft preparation, V.S.; writing—review and editing, Ž.J. and V.S.; supervision, Ž.J.; project administration, Ž.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was conducted under a research and experimental development (R&D) contract with an industrial partner located in Kaunas district, Lithuania (Contract No. F23-1, Development of a fiber sea buckthorn tea production technology using zero-waste principles, 5 January 2026).

Institutional Review Board Statement: Ethical review and approval were waived for this study, since the sensory evaluation involved healthy adult volunteers assessing conventional food products and did not constitute biomedical research under the national legislation of the Republic of Lithuania. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki.

Informed Consent Statement: Oral informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors thank the industrial partner in Kaunas district, Lithuania, for supplying the raw material and hosting part of the technological trials, and the Joint Open Access Research Center of Agriculture and Forestry (Vytautas Magnus University Agriculture Academy) for access to analytical equipment. During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist with shortening and rephrasing parts of the text; all AI-assisted content was reviewed and edited by the authors, who take full responsibility for the accuracy and integrity of the published work.

Conflicts of Interest: The authors declare no conflicts of interest.

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