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Joint Extraction of Pomegranate Peel and Seeds With Conversion of Insoluble Residues Into Protein- And Fiber-Rich Dietary Powders

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JOINT EXTRACTION OF POMEGRANATE PEEL AND SEEDS WITH CONVERSION OF INSOLUBLE RESIDUES INTO PROTEIN- AND FIBER-RICH DIETARY POWDERS

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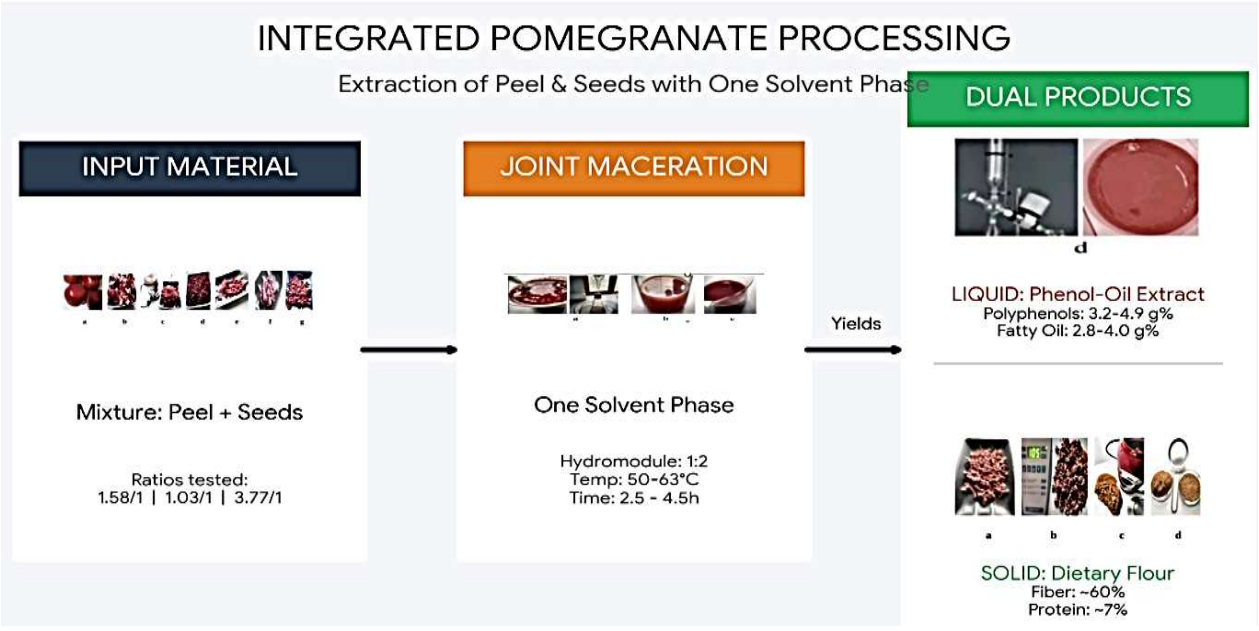
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Abstract. This study demonstrates the potential of simultaneously co-extracting ripe pomegranate peels and seeds into a single solution to effectively utilize their constituent compounds. Peels and seeds were collected from three batches of ripe pomegranates following manual peeling and the separation and juicing of the arils. The remaining residues were ground using a Reitz mill and combined at weight-to-weight (w/w) ratios of 1.58:1, 1.03:1, and 3.77:1 to formulate Mixtures 1, 2, and 3, respectively. Maceration was conducted at a solid-to-liquid ratio of 1:2 (g/mL). Mixtures 1 and 2 were processed for 4.5 hours at 63°C, whereas Mixture 3 was processed for 2.5 hours at 50-55°C with the addition of 0.015% (w/w) Fructozym MA-LG enzyme. Under these extraction conditions, the dry matter yields in the resulting solutions were 44.48 ± 0.97%, 50.56 ± 1.14%, and 61.16 ± 1.55% for Mixtures 1, 2, and 3, respectively. The primary extracts were subsequently concentrated to a dry matter content of 57.0 ± 0.5 g/100 mL, yielding 3.24 ± 0.03 to 4.93 ± 0.04 g/100 mL of polyphenols and 2.80 ± 0.02 to 4.00 ± 0.04 g/100 mL of fatty oils. Furthermore, the insoluble extraction residues were processed into dietary powders characterized by high concentrations of protein (6.25 ± 0.06 to 8.37 ± 0.09 g/100 g dry weight) and fiber (58.98 ± 0.58 to 62.60 ± 0.65 g/100 g dry weight). The transition from separate processing of raw materials to joint water extraction of a mixture of raw peel and pomegranate seeds can provide comprehensive cost savings by reducing from 30% to 50% of capital (CAPEX) and 40% of operating (OPEX) costs.

Keywords: a mixture of pomegranate peel and seeds, thermal maceration, release of component substances into solution, phenol - oil extract, protein - carbohydrate flour, dietary fiber.

Graphical abstract



Introduction

The growing interest in healthy diets and environmental sustainability has shifted focus toward the efficient utilization of food waste [1–2], particularly the peels and seeds that remain after pomegranate juice extraction.

The primary by-products of industrial pomegranate processing are the peel (a complex structure comprising the leathery pericarp, internal septa, placenta, and seed sacs) and the seeds. These seeds often exhibit a redder hue than their natural whitish color, resulting from a thin, film-like residue of the arils and brief contact with the juice during pressing.

Producers face significant challenges in managing these by-products. Although landfilling represents a simple and inexpensive disposal method, it is environmentally deleterious, contributing to the contamination of soil, groundwater, and the atmosphere. Furthermore, modern environmental legislation mandates disposal through licensed organizations, thereby increasing operational complexity. Consequently, effective recycling strategies are urgently needed to prevent waste management costs from being entirely externalized onto the primary juice product.

An analysis of current pomegranate peel processing methods indicates that solid-liquid extraction is the most prevalent approach [3]. This technique is favored not only for its high extractive yields but also for the versatile properties of the resulting extracts, which are suitable for incorporation into beverages, functional foods, and nutraceuticals [4]. Furthermore, these extracts have demonstrated the capacity to enhance food quality and extend shelf life [5]. While earlier extraction methods often relied on toxic or expensive solvents to maximize yields, contemporary manufacturers increasingly favor "green" technologies [6–7] that employ safe, GRAS-approved (Generally Recognized As Safe) solvents [8–9].

The utilization of such solvents has helped elucidate the multifaceted properties of liquid pomegranate peel extracts [10–11], while the integration of enzymatic treatments can further optimize polyphenol recovery [12–13]. Research indicates that water, ethanol, and their mixtures are the most appropriate solvents for the commercial extraction of phenolics intended for human consumption [14–16]. For instance, the total polyphenol content in aqueous peel extracts has been reported to reach 8460 mg gallic acid equivalents (GAE)/100 g dry weight (DW), significantly surpassing the yields obtained using methanol (5990 mg GAE/100 g DW) and ethanol (4530 mg GAE/100 g DW) [17]. Similarly, in the Ganesh variety, aqueous extraction yielded 438.3 ± 14.15 mg tannic acid equivalents/g [18].

The aqueous extraction of pomegranate seed oil has also been systematically investigated. The optimization of extraction parameters-including solvent-to-seed ratios (1-3:1 mL/g), pH (3-11), temperature (10-70°C), and duration (30-390 min)-yielded a maximum oil recovery of 19.3% (w/w) at a 2.2:1 mL/g ratio, pH 5.0, and 63°C for 375 minutes. Although this is lower than the yield from hexane extraction (26.8%), it significantly exceeds the yields from cold (7.0%) and hot pressing (8.6%) [19]. These findings suggest that aqueous extraction can facilitate the simultaneous recovery of both peel polyphenols and seed oil. Furthermore, studies indicate that enzymatic pre-treatment can additionally enhance the quality of the recovered oil [20-21].

Global pomegranate production totals approximately 3 million tons annually, with peels and seeds constituting roughly 54% (1.62 million tons) of this mass. Processing even a fraction of this volume necessitates diversification-specifically, strategies aimed at developing high-value products

that bolster business sustainability, generate novel revenue streams, and improve overall production efficiency [22-24].

Despite numerous proposed solutions for on-site processing, industrial adoption remains limited due to a persistent misalignment with food industry requirements. Currently, a select few specialized companies produce polyphenolic extracts and oils for herbal medicine and skincare applications using patented technologies [25–28]. However, achieving the requisite high purity often necessitates adsorption chromatography, which introduces technical complexities and substantially increases production costs. While these products are commercially viable within niche markets, they may lack the economic feasibility required for large-scale food production.

Furthermore, these highly selective technologies generate secondary waste streams (e.g., exhausted peel and defatted seeds), thereby failing to comprehensively resolve the waste management issue at juice production facilities. The separate processing of these fractions also increases overall infrastructure costs. Consequently, the potential advantages of an integrated, joint processing approach for these residues remain largely unexplored.

This study evaluates the simultaneous co-extraction of pomegranate peels and seeds, characterizing the yield and chemical composition of both the resulting solutions and the insoluble residues, and demonstrating their successful conversion into value-added products.

2 Materials and methods

2.1 Objects of research

The materials investigated in this study comprised the peels and seeds of ripe pomegranates from the 2024 harvest, as well as the resulting aqueous extracts and insoluble solid residues. The peels were isolated manually, while the seeds were recovered by pressing the separated arils using a laboratory press. Both components were individually pulverized in a Reitz mill.

As illustrated in Figure 1, the ground peel and seed fractions were combined to form composite experimental samples. These mixtures were formulated based on the natural average weight-to-weight (w/w) ratios determined from 10 randomly selected fruits across three distinct pomegranate batches: 1.58:1 (Sample 1), 1.03:1 (Sample 2), and 3.77:1 (Sample 3).



Figure1. Peel and seed extraction and pretreatment before maceration: **a**-pomegranate; **b**-hand-peeled peel; **c** – crushed peel; **d**- juicy grains; **e** –seeds; **f**- crushed seeds; **g**- a mixture of peel and seed products.

2.2 Extraction

Heated, or "hot," maceration involves processing raw plant materials in a liquid solvent at temperatures up to 65°C. The combination of grinding, heating, and agitation accelerates the extraction of bioactive substances, aromas, and flavors. This method has demonstrated high efficacy for plant materials with a high content of water-soluble components [16,29].

All extraction experiments were conducted in 750 mL glass beakers (Labdevices, St. Petersburg, Russia) utilizing a solid-to-liquid ratio of 1:2 (g/mL), ensuring sufficient solvent to

completely submerge the pulverized material. Prior to mixing, the solvent was preheated to the target temperature, which was strictly maintained throughout the maceration period. The process was performed either with the addition of the liquid enzyme preparation Fructozym MA-LG (Erbslöh Geisenheim GmbH, Germany) at **0.015%** (w/w) of the extraction mixture, or without enzymatic treatment.

Enzymatic maceration was carried out for 2.5 hours at 55°C, whereas enzyme-free maceration was performed for 4.5 hours at 63°C. Throughout the extraction process, the mixture was subjected to continuous agitation at 60 rpm using an MT-1512 mixer (China).

The majority of the resulting liquid extract was separated using a pressure-driven filtration system. The residual extract retained within the solid matrix (constituting approximately one-third or more of the total volume) was subsequently recovered utilizing a mechanical press.

The total yield of dry matter transferred into the solution was calculated using the following formula:

% yield = [(mass of dried insoluble residue) / (mass of dried starting mixture)] x 100.

The extraction yields of simple sugars, titratable acids, polyphenols, proteins, and fats were determined based on their respective mass fractions in the final extract and the initial mixture:

% yield = [(mass of substance in the resulting solution) / (mass of substance in the initial mixture)] x 100.

2.3 Transformation of formed solutions and insoluble residues

The extracts were concentrated using an evaporator to a dry matter content of 57 °Brix, either directly or following a 1-hour enzymatic clarification process at 50–55°C utilizing Fructozym P (Erbslöh Geisenheim GmbH, Germany). The application of spray drying for the concentrated extracts was also evaluated.

The insoluble residues were spread evenly across metal mesh trays and dried in a convection oven at 105°C for 5 ± 0.25 hours until an air-dry state was achieved. These dried residues were subsequently pulverized in 20-g batches for 15-20 seconds utilizing an RAF R.7124 grinder (China). Particle size distribution was determined using a Coulter counter, which quantifies changes in electrical resistance as particles pass through a micro-aperture.

2.4 Chemical analyses

- *Dry matter:* Determined in accordance with GOST 24027.2-80 by drying the prepared samples to a constant mass.
- *Simple sugars:* Quantified per GOST 8756.13-87. This method is based on the capacity of aldehyde-containing sugars to reduce Fehling's reagent (copper(II) oxide, CuO) to a reddish cuprous oxide (Cu_2O) precipitate.
- *Total acidity:* Determined via a titrimetric method according to GOST ISO 750-2013, based on titration in the presence of an indicator until the color of the analyzed solution changes. A conversion coefficient of 0.0064 was utilized to express the volume of 0.1 N NaOH solution as citric acid equivalents.
- *Crude protein:* Determined using the Kjeldahl method, applying a conversion factor of 6.25 to calculate the total protein content.
- *Crude fat:* Determined via a gravimetric method according to GOST 8756.21. This procedure involves extracting the fat with gasoline, followed by solvent removal and the subsequent determination of the fat mass in a specified aliquot of the resulting extract.
- *Minerals (ash):* Determined according to GOST 24027.2-80 by incinerating a dry sample of the starting material in a muffle furnace and weighing the resulting residue.

- *Fiber:* Determined using an enzymatic-gravimetric method in accordance with GOST 34844-2002, a standard applicable to special-purpose food products, biologically active additives, and dietary supplements.
- *Total polyphenols:* Determined according to GOST 24027.2-80, based on the titration of unreacted indigo carmine with a 0.1 N $KMnO_4$ (potassium permanganate) solution following the oxidation of phenolic substances. Because other compounds also react with permanganate, all substances oxidized by this reagent are titrated first. A second titration is then performed on the extract residue after treatment with activated carbon, which selectively adsorbs only polyphenols. The total phenolic content is determined from the difference in the volume of permanganate consumed between the first and second oxidations. A coefficient of 0.004157 is used to convert milliliters of 0.1 N KMnO4 solution into grams of phenols. This underlying principle also forms the basis of Article 1.5.3.0008.18 of the Russian Pharmacopoeia (XIV edition), which outlines the methodology for quantifying tannins in medicinal raw materials.

2.5 Primary data processing

Data were analyzed using standard descriptive statistics, with the results of repeated measurements expressed as the mean and standard deviation. A significance level of 5% ($p < 0.05$) was established for all tests. All statistical analyses were performed using IBM SPSS Statistics software, version 26 (IBM Corp., Armonk, NY, USA).

3 Results

3.1 Thermal maceration without enzyme involvement

3.1.1 The component composition of primary extracts from seed maceration and a mixture of peel and seeds of pomegranate sample number **1**

An analysis of 10 randomly selected fruits from Sample 1 determined that an average fruit contained 71.1 ± 1.5 g (29.7 ± 0.63% of the total weight) of peel, 168.5 ± 3.5 g (70.3 ± 1.5%) of arils, and 45.0 ± 0.9 g (18.8 ± 0.38%) of actual seeds. Based on the 1.58:1 (w/w) ratio between the peel and the actual seeds, processing 1 ton of these pomegranates would yield approximately 515 kg of juice, leaving 297 kg of peel and 188 kg of seeds as by-products.

Table 1 presents the component composition of the isolated peel and seeds from Sample 1, as well as a composite mixture formulated at their naturally occurring 1.58:1 (w/w) ratio.

Table 1. Component composition of **P**, **BS** and **P+BS** 1.58/1 (weight/weight) of pomegranate sample number **1**, G/100 g of crude weight.

Symbols: **P** – peel, **BS** – seeds themselves, **P+BS**- a mixture of peel and seeds.

Components	P	BS	P+BS
Dry substances	40.00±0.55	41.32±0.58	40.51±0.52
Sucrose	0.66 ±0.01	0.00	0.40±0.01
Monosaccharides	10.08±0.13	9.05±0.15	9.68±0.14
Titrated acids (in terms of citric acid)	4.39± 0.06	1.35±0.02	3.21±0.04
Crude protein (N x 6.25)	2.50±0.04	5.13±0.05	3.52±0.05
Crude fat	2.80±0.03	7.30±0.10	4.54±0.05
Fibers	13.32±0.19	17.04±0.22	14.76±0.20
Mineral substances	0.75±0.01	0.80±0.01	0.77±0.01

Substances capable of reacting with $KMnO_4$:			
Total	5.50±0.09	0.65±0.01	3.62±0.05
Polyphenols	3.60±0.04	0.25±0.01	2.28±0.03
p-value	0.05	0.05	0.05

The data indicate that the **P** and **BS** fractions of this pomegranate sample differ significantly in the quantitative composition of several compounds with potential industrial utility. Specifically, **P** is notably richer in monosaccharides, titratable acids, and polyphenols (10.08 ± 0.13, 4.39 ± 0.06, and 3.60 ± 0.04 g/100 g, respectively) compared to **BS** (9.05 ± 0.15, 1.35 ± 0.18, and 0.25 ± 0.01 g/100 g, respectively). Conversely, **BS** exhibits substantially higher concentrations of protein and fat (5.13 ± 0.05 and 7.30 ± 0.10 g/100 g, respectively) than **P** (2.50 ± 0.04 and 2.80 ± 0.03 g/100 g, respectively).

Table 2 presents the chemical composition of the solutions resulting from a 4.5-hour maceration of isolated **BS** and a 1.58:1 (w/w) **P**+**BS** mixture from Sample 1, utilizing a solid-to-liquid ratio of 1:2 (g/mL) at 63°C. Additionally, it details the relative percentage contributions of the **P** and **BS** fractions to the total mass of each substance extracted into the solution from 258 g of the **P**+**BS** mixture (158 g peel + 100 g seeds).

Table2. Component composition of solutions from 4.5-hour maceration of **BS** and **P+BS** [1.58/1 (weight/weight)] of the pomegranate sample number **1** at a 1:2 hydromodule and a temperature of 63 °C.

Components	**Maceration solutions:**		
	BS (100 g)	P+BS (258 g)	
	G/100 ml	G/100 ml	The ratio between the P and BS components of the total mass of the part of the substance that came out of the mixture into solution,%/%
Dry substances	8.27±0.20	9.30±0.10	64.43/35.57
Monosaccharides	3.88±0.09	3.53±0.07	55.98/44.02
Titrated acids (in terms of citric acid)	0.52±0.01	1.25±0.04	83.36/16.64
Crude protein (N x 6.25)	1.26±0.03	0.80±0.02	37.00/63.00
Crude fat	1.15±0.02	0.73±0.02	36.99/63.01
Fibers	1.05±0.02	0.32±0.01	72.33/27.67
Mineral substances	0.15±0.01	0.17±0.01	64.71/35.29
Substances capable of reacting with $KMnO_4$:			
Total	0.26±0.01	2.50±0.04	95.84/4.16
Polyphenols	0.09±0.01	0.79±0.02	67.18/32.82
p-value	0.05	0.05	0.05

Note. *Extract yield: 200 ml/100 g of BS; 500 ml/258 g of P+BS mixture.*

The presented data indicate that the solids concentration in the solution following the maceration of 100 g of **BS** was 8.27 ± 0.20 g/100 mL, whereas the solution derived from 258 g of the **P**+**BS** mixture had a concentration of 9.30 ± 0.10 g/100 mL. Considering the total volumes of these extracts—200 mL for the 100 g **BS** sample and 500 mL for the 258 g **P**+**BS** sample - the total

solids yield was 16.54 g per 100 g of **BS** and 46.5 g per 258 g of the **P**+**BS** mixture (equivalent to 18.0 g per 100 g of the mixture).

This higher solids yield in the **P**+**BS** extract cannot be attributed to a greater initial concentration of total solids in the raw material; in fact, the initial solids concentration was higher in the isolated **BS** (41.32 ± 0.58 g/100 g fresh weight) than in the **P**+**BS** mixture (40.51 ± 0.52 g/100 g fresh weight).

Rather, this difference arises because the **P**+**BS** mixture was initially richer in easily soluble solid fractions - specifically monosaccharides, acids, polyphenols, and soluble fibers- which transfer into the solution more rapidly and completely than other components.

Furthermore, the data regarding the respective contributions of the **P** and **BS** components to mass transfer reveal that of the total solids extracted into the solution from the 258 g **P**+**BS** mixture, the **P** fraction accounted for 64.43%, while the **BS** fraction contributed 35.57%.

This ratio is derived from the composition of the 258 g **P**+**BS** mixture, which contained 100 g of **BS**. Based on the extraction yield of the isolated **BS** (8.27 g/100 mL across a 200 mL volume), the **BS** component contributed 16.54 g of dry matter to the solution. This 16.54 g constitutes 35.57% of the total 46.5 g of dry matter extracted from the entire mixture (calculated as 9.30 g/100 mL across a 500 mL volume).

Regarding the total mass of specific compounds extracted into the solution, the ratio of the **P** to **BS** contributions was 55.98:44.02 (%) for monosaccharides, 83.36:16.64 (%) for titratable acids, and 67.18:32.82 (%) for total polyphenols.

Conversely, of the total protein and fat extracted from the mixture, the ratio of the **P** to **BS** contributions favored the **BS** component (37.00:63.00 (%) and 36.99:63.01 (%), respectively).

This disparity is attributed to the initially higher concentrations of protein and fat in **BS** compared to **P**.

From a practical perspective, a more significant indicator is the extraction yield of individual compounds from both the isolated **BS** and the **P**+**BS** mixture, expressed as a percentage of their initial mass in the raw material.

Table 3. Extraction yields of specific compounds from isolated **BS** and the 1.58:1 (w/w) **P**+**BS** mixture from Sample **1**, following a 4.5-hour maceration at 63°C utilizing a 1:2 (g/mL) solid-to-liquid ratio.

Components	**The yield:**	
	% of the total mass of the substance in 100 g **BS**	% of the total mass of the substance in 258 g **P+BS** 1.58/1 (weight/weight)
Dry substances	40.03±0.99	44.48±0.97
Monosaccharides	85.75 ±2.12	70.68±1.75
Titrated acids (in terms of citric acid)	77.04±1.91	75.48±1.55
Crude protein (N x 6.25)	49.12± 1.21	44.05±0.93
Crude fat	31.50±0.78	32.15±0.66
Fibers	12.32±0.30	10.97±0.23
Mineral substances	37.50±0.92	42.71±0.88
Substances capable of reacting with $KMnO_4$:		
Total	80.00±1.97	80.30±1.65
Polyphenols	72.00±1.78	67.18±1.38
p-value	0.05	0.05

As shown in Table 3, under these extraction conditions, the yield of dry matter transferred into the solution was 40.03 ± 0.99% and 44.48 ± 0.97% of the total initial weight for the 100 g **BS** and 258 g **P**+**BS** samples, respectively.

The extraction yields for specific compounds, relative to their initial mass in the 100 g **BS** and 258 g **P**+**BS** samples, were as follows: monosaccharides (85.75 ± 2.12% and 70.68 ± 1.75%), titratable acids (77.04 ± 1.91% and 75.48 ± 1.55%), and total polyphenols (72.00 ± 1.78% and 67.18 ± 1.38%), respectively.

*3.1.2 Component composition of primary extracts obtained via thermal maceration of the **P**+**BS** mixture from Sample 2*

Technical analysis of Sample **2** (n = 10) revealed that an average fruit weighing 239.0 ± 7.0 g consisted of 55.2 ± 1.6 g (23.1%) peel and 183.8 ± 5.4 g (76.9%) arils. The arils further yielded 53.8 ± 1.6 g (22.5% of the total fruit weight) of actual seeds and 130.0 ± 3.8 g (54.4%) of juice. Consequently, the weight-to-weight (w/w) ratio between the peel and the actual seeds in this sample was 1.03:1.

Following a 4.5-hour maceration of 106.6 g of the **P**+**BS** mixture (1.03:1, w/w) utilizing a 1:2 (g/mL) solid-to-liquid ratio at 63°C, the extraction yields of its constituent compounds into the solution were as presented in Table 4.

Table 4. Component composition of the 1.03:1 (w/w) **P**+**BS** mixture from Sample **2** and the resulting solution following a 4.5-hour maceration at 63°C utilizing a 1:2 (g/mL) solid-to-liquid ratio.

Components	P+BS mixture, G/100 g of raw mass	Solution, G/100 ml	Yield of the substance in solution, % of the total mass of the substance in 106.6 g of the crude mixture
Dry substances	42.92±0.50	9.46±0.12	50.56±1.14
Sucrose	0.52±0.01	0.10 ±0.01	45.45 ±1.02
Monosaccharides	14.59±0.17	4.85±0.06	78.41±1.76
Titrated acids (in terms of citric acid)	4.17 ±0.04	1.33 ±0.02	75.34±1.69
Crude protein (N x 6.25)	3.08±0.04	0.78±0.02	58.04± 1.03
Crude fat	4.70±0.05	0.60±0.01	30.12 ±0.67
Fibers	10.04±1.26	0.28±0.01	6.57±0.15
Mineral substances	0.84 ±0.01	0.15±0.01	42.69±0.96
Substances capable of reacting with $KMnO_4$:			
Total	4.98±0.06	1.37±0.02	64.96±1.46
Polyphenols	2.79±0.03	0.77±0.01	65.20±1.47
p-value	0.05	0.05	0.05

Note. *Extract yield: 250 ml/106.6 g of crude mixture.*

The data show that the extraction yields into the solution, relative to the initial total mass of each substance in 106.6 g of the 1.03:1 (w/w) **P**+**BS** mixture, were 78.41 ± 1.76% for monosaccharides, 75.34 ± 1.69% for titratable acids, 65.20 ± 1.47% for total polyphenols, and 6.57 ± 0.15% for fibers (predominantly soluble pectin).

Additionally, 58.04 ± 1.03% of the protein and 30.12 ± 0.67% of the crude fat were released into the solution, which subsequently complicated the separation process.

A comparison of the data in Tables 3 and 4 reveals that a greater proportion of dry matter was extracted into the solution from the 1.03:1 **P**+**BS** mixture in this experimental trial (50.56 ± 1.14% of the initial total weight) than from the 1.58:1 (w/w) **P**+**BS** mixture utilized in the previous experimental variants (44.48 ± 0.97%). This difference can be attributed to the fact that the 1.03:1 (w/w) **P**+**BS** mixture from this pomegranate sample initially contained a higher concentration of solids (42.92 ± 0.50 g/100 g fresh weight) compared to the 1.58:1 (w/w) **P**+**BS** mixture from Sample 1 (40.51 ± 0.52 g/100 g fresh weight).

3.2 Thermal maceration of the P+BS mixture from pomegranate Sample 3 with the addition of the enzyme Fructozym MA-LG

In pomegranate Sample **3**, the average fruit weight was 241.0 ± 9.0 g, with the peel accounting for 37.6 ± 1.41% of this mass. The mass ratio between the **P** and **BS** fractions was identical to that presented in Table 5.

Table5. Indicators of the technical composition of the sample of pomegranates number **3** using the example of one average fruit.

Part of the fetus	Gram	% of the total weight of the fetus	Ratio between P and BS (weight/weight)
P	90.5±3.4	37.6±1.41	3.77/1
Grains with juice	150.5±5.6	62.4±2.32	
Juice	126.5±4.7	52.4±1.95	
BS	24.0±0.9	10.0±0.37	

Following a 2.5-hour maceration of 114.5 g of the **P**+**BS** mixture (3.77:1, w/w) from this pomegranate sample, utilizing a 1:2 (g/mL) solid-to-liquid ratio at 50–55°C with the addition of 0.15% Fructozym MA-LG enzyme, the extraction yields of its constituent compounds into the solution were as presented in Table 6.

Table 6. Component composition of the 3.77:1 (w/w) **P**+**BS** mixture from pomegranate Sample **3** and the primary extract resulting from a 2.5-hour maceration at 50–55°C utilizing a 1:2 (g/mL) solid-to-liquid ratio with the addition of 0.15% Fructozym MA-LG enzyme.

Components	Initial crude mixture, G/100 G of crude mass	Solution, G/100 ml	Yield of the substance in solution, % of the total mass of the substance in 114.5 G P+BS
Dry substances	42.21 ±0.40	12.91±0.20	61.16±1.55
Sucrose	0.85± 0.01	0.31±0.01	63.92±1.62
Monosaccharides	18.93±0.18	8.43±0.12	77.80±1.97
Titrated acids (in terms of citric acid)	3.16±0.03	1.47±0.02	72.24±1.83
Crude protein (N x 6.25)	2.16 ±0.03	0.40±0.01	36.57±1.11
Crude fat	3.92±0.04	0.80±0.02	40.81±0.58
Fibers	7.79±0.07	0.15 ±0.01	3.36±0.08
Mineral substances	0.64±0.01	0.13±0.01	17.80±0.45
Substances capable of reacting with $KMnO_4$:			
Total	4.76 ±0.04	1.92 ±0.03	70.46±1.79
Polyphenols	3.21±0.02	1.33±0.02	72.28±1.83
p-value	0.05	0.05	

Note. *Extract yield: 200 ml/114.5 g of crude mixture.*

As indicated by the data, the extraction yields for this variant, expressed as a percentage of the total initial mass of each substance in the starting material, were 77.80 ± 1.97% for monosaccharides, 72.24 ± 1.83% for titratable acids, 72.28 ± 1.83% for total polyphenols, 3.36 ± 0.08% for fibers, 36.57 ± 1.11% for protein, and 40.81 ± 0.58% for fat.

A comparison of the effectiveness of non-enzymatic (previous variants) and enzymatic (current variant) maceration revealed that, despite operating at a milder temperature and for a shorter duration, the incorporation of an enzyme significantly increased the extraction yields of dry matter and fat into the solution.

Specifically, while the two previous non-enzymatic variants yielded 44.48 ± 0.97% and 50.56 ± 1.14% of total solids, and 32.15 ± 0.66% and 30.12 ± 0.67% of fat, the enzymatic maceration variant achieved substantially higher dissolution rates, recovering 61.16 ± 1.55% of total solids and 40.81 ± 0.58% of fat.

Concurrently, lower amounts of protein (36.57 ± 1.11%) and fibers (3.36 ± 0.08%) were released into the solution during enzymatic maceration compared to the non-enzymatic variants (which yielded 45.45 ± 0.93% and 58.04 ± 1.03% for protein, and 10.97 ± 0.23% and 6.57 ± 0.15% for fibers, respectively).

Consequently, the application of the enzyme contributed to a partial, though incomplete, clarification of the resulting solutions.

Given the substantial quantity of oil released into the liquid phase, it can be subsequently isolated as a distinct byproduct using centrifugation.

3.3 Concentration of the primary extract

The separation and subsequent processing of the resulting solutions into intermediate and final products are illustrated in Figure 2.

Because the solution was highly viscous and difficult to separate from the macerated raw material, it was forcibly extracted using a pump. This system generated pressure between the extraction vessel and the receiving container, driving the liquid phase through a filtration layer (Fig. 2, **a**). The residual extract trapped within the solid matrix was recovered using a mechanical pressing device, and the two liquid fractions were subsequently pooled to yield the total extract volume (Fig. 2, **b**).

The combined solution was then directed to the evaporation stage.

Alternatively, prior to evaporation, the solution could be transferred to a heated mixing vessel. There, it was continuously agitated at 60 rpm for 1 hour at 50–55°C, with the addition of 0.015% Fructozym P enzyme (Fig. 2, **c**) to eliminate turbidity caused by soluble pectins.

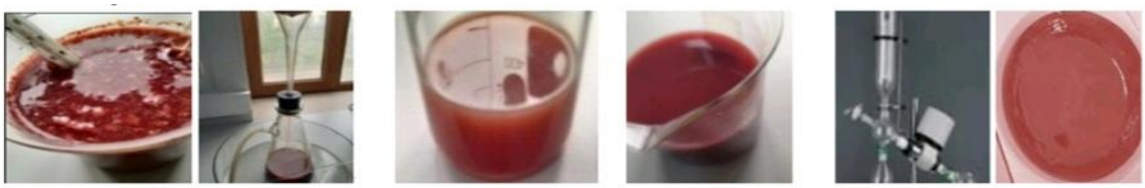


Figure 2. Separation and processing of the primary extract: (**a**) the extraction mixture and a custom-built system for separating the resulting solution; (**b**) the separated solution; (**c**) solution (b) following enzymatic treatment; and (**d**) solution (c) after concentration in an evaporator to a dry matter content of 57 g/100 g.

The initial or clarified extract was transferred to a vacuum evaporator, where it was concentrated at 50–60°C under a vacuum of 600–650 mmHg until a dry matter content of 57% was achieved (Fig. 2, **d**).

The dry matter content was monitored using a refractometer.

Table 7 presents the results of the chemical evaluation of laboratory-scale concentrated extracts obtained from the maceration of isolated **BS** from Sample 1 and the **P**+**BS** mixtures from Samples 1–3.

Table 7. Component composition (g/100 mL) of concentrated extracts obtained from the maceration of isolated **BS** (Sample **1**) and **P**+**BS** mixtures (Samples **1–3**) utilizing a 1:2 (g/mL) solid-to-liquid ratio.

Symbols: **a** - *concentrate derived from a 4.5-hour maceration of isolated* **BS** *from pomegranate Sample* **1** *at 63°C;* **b** - *concentrate derived from a 4.5-hour maceration of the 1.58:1 (w/w)* **P**+**BS** *mixture from pomegranate Sample* **1** *at 63°C;* **c** - *concentrate derived from a 4.5-hour maceration of the 1.03:1 (w/w)* **P**+**BS** *mixture from pomegranate Sample* **2** *at 63°C (the primary extract was treated with Fructozym P enzyme for 1 hour at 50-55°C prior to concentration);* **d** - *concentrate derived from a 2.5-hour maceration of the 3.77:1 (w/w)* **P**+**BS** *mixture from pomegranate Sample* **3** *at 50-55°C, with the addition of 0.015% Fructozym MA-LG enzyme to the extraction mixture.*

Components	a	b	c	d
Dry substances	57.00±0.50	57.00±0.20	57.00±0.20	57.00±0.20
Monosaccharides	26.09±0.22	32.09±0.28	29.21±0.26	34.97±0.31
Sucrose	0.00	1.14±0.01	0.50±0.01	1.23±0.01
Titrated acids (in terms of citric acid)	3.50±0.04	6.81±0.07	7.83±0.06	5.84±0.05
Substances capable of reacting with $KMnO_4$:				
Total	1.67±0.02	5.92±0.05	8.00±0.07	7.04±0.06
Polyphenols	1.27±0.01	3.24 ±0.03	4.35±0.04	4.93±0.04
Fat	7.56±0.06	4.00±0.04	3.62±0.03	2.80±0.02
Protein (N x 6.25)	8.08±0.07	4.40±0.03	4.20±0.04	1.70±0.02
p-value	0.05	0.05	0.05	0.05

As demonstrated by these data, the extracts obtained via this method retain all constituent compounds of the initial mixture, most notably the biologically active polyphenols from the peel and the seed oil.

These concentrated extracts are highly viscous liquids suitable for bottling in glass vials as ready-to-use, non-sterile herbal preparations.

A comparison of the component compositions of the **BS** (**a**) and **P**+**BS** (**b**, **c**, **d**) concentrates reveals significant differences in the quantitative content of compounds that impart specialized nutritional value.

The concentrated **BS** (**a**) extract exhibits a significantly lower polyphenol content (1.27 ± 0.01 g/100 mL) compared to the **P**+**BS** (**b**, **c**, **d**) extracts, which range from 3.24 ± 0.03 g/100 mL to 4.93 ± 0.04 g/100 mL.

Conversely, the fatty oil concentration in the **BS** (**a**) extract is substantially higher (7.56 ± 0.06 g/100 mL) than in the **P**+**BS** (**b**, **c**, **d**) extracts, which contain between 2.80 ± 0.02 g/100 mL and 4.00 ± 0.04 g/100 mL.

Furthermore, the **BS** (**a**) concentrate contains considerably more protein (8.08 ± 0.07 g/100 mL) than the concentrated **P**+**BS** (**b**, **c**, **d**) extracts, which range from 1.70 ± 0.02 g/100 mL to 4.40 ± 0.03 g/100 mL.

Given its color and consistency-attributes primarily influenced by its high protein and fat content (Fig. 3)-the **BS** (**a**) concentrate would be more accurately characterized as "pomegranate milk."



Figure 3. Concentrated extract from maceration of **BS** sample of pomegranates **1**.

Under the conditions of this study, 44.48 ± 0.97% of the total solids, 44.05 ± 0.93% of the protein, 32.15 ± 0.66% of the fat, and 10.97 ± 0.23% of the fiber were extracted into the solution from mixture **1**. The corresponding dissolution yields for mixture **2** were 58.04 ± 1.03%, 30.12 ± 0.67%, 30.12 ± 0.67%, and 6.57 ± 0.15%, respectively; and for mixture **3**, they were 61.16 ± 1.55%, 36.57 ± 1.11%, 40.81 ± 0.58%, and 3.36 ± 0.08%, respectively.

The concentrations of monosaccharides (ranging from 29.21 ± 0.26 g/100 mL to 34.97 ± 0.31 g/100 mL) and titratable acids (ranging from 5.84 ± 0.05 g/100 mL to 7.83 ± 0.06 g/100 mL) are exceptionally high in the concentrated **P**+**BS** (**b**, **c**, **d**) extracts, indicative of their significant nutritional value. Conversely, these high concentrations reduce the relative purity of the extracts concerning their primary bioactive components—namely, the polyphenols and the fatty oil fraction.

The feasibility of converting the concentrated extracts into a powder was evaluated using a spray dryer. The extracts were fed into the system via a pump operating at pressures between 50 and 200 bar, with an inlet air temperature of 150–200°C and an outlet temperature of 60–90°C.

The results indicated that transforming these extracts into a dry powder (with a particle size range of 20 to 800 microns) is highly challenging. This difficulty is primarily attributed to their high viscosity and the presence of sticky fatty oils. A more viable physical form for these processed extracts is a thick, viscous liquid, similar in texture to thickened liquid medications designed for safe swallowing.

Furthermore, if required by specific business or manufacturing objectives, these viscous extracts can be subjected to centrifugation to isolate the pure pomegranate seed oil.

3.4 Conversion of insoluble residue

Figure 4 illustrates the intermediate and final products of the maceration residue conversion process. Initially, the crude insoluble residue (Fig. 4, **a**) is dried to an air-dry state (Fig. 4, **b**) utilizing a heated air stream (vertical or alternative convective dryers equipped with ventilation systems are suitable for this purpose). The dried residue is subsequently pulverized into particles ranging from 0.3 to 0.8 mm (Fig. 4, **c**) and fractionated through a 0.5-mm mesh sieve to separate the particles by size (Fig. 4, **d**).



Figure 4. Crude insoluble residue and the intermediate and final products of its conversion: (**a**) crude residue; (**b**) dried residue; (**c**) dried residue following pulverization; and (**d**) two fractions obtained by separating the pulverized residue through a 0.5-mm sieve.

The rationale for employing such a straightforward processing method for the dried and pulverized residue - namely, fractionation through a 0.5-mm sieve - is based on the following

considerations. Because the particle size distribution within the resulting powder is highly heterogeneous, it was necessary to determine which structural components were more susceptible to pulverization. The hypothesis was that certain components of the dried residue, such as the seed kernels (where the majority of the protein is concentrated), would pulverize more readily than the coarser, fiber-rich structures. To investigate this, the primary powders obtained from drying and subsequent pulverization in a standard grinder for 15–20 seconds were analyzed. It was observed that 30–35% of the powder consisted of a coarse fraction (particles larger than 0.5 mm), which predominantly comprised fragments of the peel (internal septa and pericarp membranes) and aril films. Conversely, the finer fraction contained the more readily pulverized- and consequently more nutritionally valuable - seed kernel particles.

Analyses showed that this separation converted nearly all protein from the initial powder into the fine fraction.

Tables 8 and 9 present the component composition of the dry residues (**BS** and **P+BS**) of pomegranate sample No. 1 and two fractions obtained by sieving through a 0.5 mm mesh. After 4.5 hours of maceration at a 1:2 liquid-to-solid ratio (hydromodule) and 63 °C, the protein content in the insoluble **BS** residue was 6.51 ± 0.05 g/100 g dry weight, while in the insoluble residue of the **P+BS** mixture, it was 3.57 ± 0.03 g/100 g dry weight. In the insoluble **BS** residue and the **P+BS** mixture, the fiber content remained high - 60.23 ± 0.50 g/100 g and 53.00 ± 0.54 g/100 g dry weight, respectively.

Although protein and fiber can be consumed together, certain applications require higher product purity. This necessitates redistributing these substances by transferring protein to one fraction of the powder and fiber to another.

Data from Tables 8 and 9 indicate that this can be achieved by separating the initial powder into two fractions with particle sizes of <0.5 mm and >0.5 mm.

Table 8. Component composition of the dry solid residue after 4.5 hours of crude **BS** maceration (pomegranate sample No. 1) at a 1:2 liquid-to-solid ratio and 63 °C

*Symbols: **a** - insoluble residue before separation on a 0.5 mm sieve; **b** - fine fraction with a particle size <0.5 mm; **c** - coarse fraction with a particle size >0.5 mm.*

Components	G/100 g of dry weight		
	a	b	c
Sucrose	0.00	0.00	0.00
Monosaccharides	5.19±0.04	5.89±0.05	4.39±0.04
Titrated acids (in terms of citric acid)	1.27±0.01	1.56±0.01	0.94±0.01
Protein (N x 6.25)	6.51±0.05	11.11±0.10	1.32±0.01
Fat	24.22±0.23	25.68 ±0.23	22.56±0.20
Fibers	60.23±0.50	53.39±0.52	68.04±0.65
Mineral substances	2.06±0.02	1.72±0.02	2.44±0.02
Substances capable of reacting with $KMnO_4$:			
Total	0.54±0.01		0.31±0.01
Polyphenols	0.28±0.01	0.74±0.01 0.28±0.01	0.28±0.01
p-value	0.05	0.05	0.05

Note. *The yield of the crude residue is 68.8 g/100 g of raw* **BS***, and the dry residue is 24.8 g/100 g of raw* **BS** *[fine fraction/coarse fraction 1.14/1 (weight/weight)].*

As shown in Table 8, the protein content in the two fractions of the dried residue from the **BS** maceration of pomegranate sample No. 1 was 11.11 ± 0.10 g/100 g dry weight for the fine fraction and 1.13 g/100 g dry weight for the coarse fraction. This indicates that the protein concentration in the fine fraction is approximately nine times higher than in the coarse fraction.

As shown in Table 9, the protein content in the two fractions of the dried residue from the maceration of the **P+BS** mixture (pomegranate sample No. 1) was 6.25 ± 0.06 g/100 g dry weight for the fine fraction and 0.63 ± 0.01 g/100 g dry weight for the coarse fraction. This demonstrates that the fine fraction contains 9.9 times more protein than the coarse fraction.

Table 9. Component composition of the dehydrated solid residue after 4-hour maceration of crude **P+BS** (1.58/1 w/w) from pomegranate sample No. **1** at a 1:2 liquid-to-solid ratio and 63 °C.

Symbols: ***a*** *– insoluble residue before separation on a 0.5 mm sieve;* ***b*** *– fine fraction with a particle size <0.5 mm;* ***c*** *– coarse fraction with a particle size >0.5 mm.*

Components	**G/100 g of dry weight**		
	a	**b**	**c**
Sucrose	1.40±0.01	2.45±0.02	0.25±0.01
Monosaccharides	13.13±0.12	15.80±0.17	10.20±0.09
Titrated acids (in terms of citric acid)	3.66±0.03	4.20±0.04	2.75±0.02
Protein (N x 6.25)	3.57±0.03	6.25±0.06	0.63±0.01
Fat	17.75±0.18	19.46±0.20	15.87±0.17
Fibers	53.00±0.54	44.81±0.45	62.11±0.64
Mineral substances	2.03±0.02	1.60±0.01	2.51±0.02
Substances capable of reacting with $KMnO_4$:			
Total	5.53±0.045	5.43±0.04	5.68±0.06
Polyphenols	3.44± 0.03	3.20±0.02	3.71±0.04
p-value	0.05	0.05	0.05

Note. *The yield of the crude residue is 193.8 g/258 g of raw* **P+BS***, and the dry residue is 55.6 g/258 g of raw* **P+BS** *[fine fraction/coarse fraction 1.1/1 (weight/weight)].*

To determine the differences in the specific values of these and other indicators regarding the component composition of the two powders obtained by separating the dry insoluble residues from the maceration of **P+BS** (pomegranate samples No. **2** and **3**), refer to the data in Tables 10–11.

The results indicate that these two powder fractions, obtained from the residues of the **P+BS** mixtures (pomegranate samples No. **2** and **3**), contain:

- fine-grained fraction: protein 7.06 ± 0.07 - 8.37 ± 0.09 g/100 g dry weight; fiber 37.95 ± 0.40 - 38.39 ± 0.37 g/100 g dry weight;
- coarse-grained fraction: protein 1.05 ± 0.01 - 1.13 ± 0.01 g/100 g dry weight; fiber 58.98 ± 0.58 - 62.63 ± 0.65 g/100 g dry weight.

Consequently, separation in these cases also led to a significant increase in protein content and a decrease in fiber content in the fine fraction. Conversely, the coarse fraction exhibited a decrease in protein content and an increase in fiber content.

The tables below further demonstrate that, in addition to protein, the majority of monosaccharides, acids, and fatty oils were also concentrated in the fine fraction.

Table10. Component composition of the dehydrated solid residue after 4-hour maceration of crude **P+BS** (1.03/1 w/w) from pomegranate sample No. **2** at a 1:2 liquid-to-solid ratio and 63 °C.

*Symbols: **a**- insoluble residue before separation on a 0.5 mm sieve; **b** - fine fraction with a particle size <0.5 mm; **c** -coarse fraction with a particle size >0.5 mm.*

Components	G/100 g of dry weight		
	a	b	c
Sucrose	1.41±0.01	1.80±0.01	0.48±0.01
Monosaccharides	15.54±0.17	17.85±0.19	10.00±0.09
Titrated acids (in terms of citric acid)	5.05±0.05	5.95±0.06	2.90±0.04
Protein (N x 6.25)	5.31±0.03	7.06 ±0.07	1.13±0.01
Fat	16.18±0.15	17.40±0.16	13.27±0.12
Fibers	45.00±0.45	37.95±0.40	62.63 ±0.65
Mineral substances	2.38±0.02	1.85±0.01	3.65±0.04
Substances capable of reacting with $KMnO_4$:			
Total	9.07±0.09	9.14±0.10	4.94±0.05
Polyphenols	4.81 ±0.05	5.68±0.07	2.72±0.03
p-value	0.05	0.05	0.05

Note.** The yield of the crude residue is 97.9 g/109 g of raw* **P+BS, and the dry residue is 21.5 g/109 g of raw* **P+BS** *[fine fraction/coarse fraction 2.4/1 (weight/weight)].*

Table 11. Component composition of the dehydrated solid residue from 2.5-hour maceration of crude **P+BS** 3.96/1 (weight/weight) of pomegranate sample number **3** at a 1:2 (g/ml) hydromodule and a temperature of 55 °C with the addition of 0.015% Fructozym MA-LG enzyme to the extraction mixture.

*Symbols: **a** - insoluble residue before separation on a sieve with 0.5 mm holes; **b**- fine fraction with a particle size of <0.5 mm; **c**- coarse fraction with a particle size of >0.5 mm.*

Components	G/100 g of dry weight		
	a	b	c
Sucrose	1.59±0.01	2.00±0.01	0.00
Monosaccharides	22.56±0.24	24.00±0.26	18.60±0.20
Titrated acids (in terms of citric acid)	5.29 ±0.04	6.25±0.07	2.65±0.03
Protein (N x 6.25)	6.43±0.05	8.37±0.09	1.05±0.01
Fat	10.89 ±0.13	11.07±0.13	10.38±0.15
Fibers	43.75 ±0.42	38.39±0.37	58.98±0.58
Mineral substances	2.19±0.02	1.77±0.02	3.40±0.03
Substances capable of reacting with $KMnO_4$:			
Total	7.30±0.08	8.15±0.07	4.94±0.05
Polyphenols	4.81 ±0.05	5.60±0.06	2.64±0.03
p-value	0.05	0.05	0.05

Note.** The yield of the crude residue is 60.0 g/114.5 g of raw* **P+BS, and the dry residue is 21.3 g/114.5 g of raw* **P+BS** *[fine fraction/coarse fraction 2.78/1 (weight/weight)].*

Consequently, the primary result of restructuring the dry residue powders of **P+BS** mixtures from pomegranate samples **1**, **2**, and **3** was that the majority of the protein, titratable acids, and

monosaccharides originally present partitioned into the fine fraction, while the coarse fraction became significantly enriched in fiber.

4 Techno economic considerations for industrial implementation

The transition from separate processing of raw materials to joint water extraction of a mixture of raw peel and pomegranate seeds can provide comprehensive cost savings by reducing capital (CAPEX) and operational (OPEX) costs.

In comparison with traditional industrial analogues, which require the creation of two isolated technological sites (for the peel and for seeds) and separate plants for the extraction and extraction of individual substances, the economic effect consists of the following key factors:

1. Reduction of capital investment (CAPEX)

• Elimination of duplicate equipment: Instead of two parallel drying and grinding lines (separately for the peel and separately for the seeds), one process stream is created. This eliminates the need to purchase, install, and maintain a second set of drying drums, crushers, and mills.

• Avoiding expensive extraction plants: There is no need for a highly specialized plant for extracting individual substances (for example, co2 extractors or systems for working with organic solvents), since the hydro-lipophilic liquid concentrate is obtained as part of a single aqueous extraction process.

• Saving production space: The cost of building and equipping workshops is reduced, since one combined site occupies a significantly smaller area than two separate ones.

2. Reduced operating costs (OPEX)

• Energy saving at the drying stage: Processing raw materials in raw form (a mixture of raw peel and seeds) allows you to transfer the energy-intensive drying process from the feedstock to the post-extraction residue (pulp). The volume of moisture evaporated and the cost of thermal energy are reduced, as part of the soluble substances passes into a liquid concentrate.

• Optimization of the payroll: Significantly fewer operators and technical personnel are required to maintain one combined production line than for two separate production sites.

• Savings on solvents and ecology: Using clean water as an extractant instead of organic solvents (alcohol, hexane, etc.) reduces the cost of the raw material cost of the process and eliminates the cost of solvent regeneration systems, as well as reduces fees for environmental risks and disposal of hazardous waste.

3. Increased profitability and waste-free

• Deep waste-free recycling: The method converts juice production waste into highly liquid products: hydro-lipophilic liquid concentrate (rich in polyphenols and fatty acids) and protein-containing powders from the post-extraction residue.

• Increased added value: Instead of selling raw meal or losing valuable components during separate drying, the company receives ready-made components with high margins for the pharmaceutical, cosmetics and food industries.

When extracting the peel and seeds together, the total cost savings can range from 30% to 50% at the capital construction stage and up to 40% on daily operating costs compared to separate processing schemes for pomegranate components.

5 Discussion

During the juice extraction process from *Punica granatum L.* fruit, the succulent seeds are first separated from the **P**; the juice is then expressed from the seeds, leaving the **BS**. The economic viability of this process is heavily influenced by the balance between the juice and the solid fruit components, which varies significantly depending on the pomegranate variety [30]. A previous study of 24 varieties and forms of Azerbaijani pomegranates found that the mass fraction of seeds ranged from 46.73–75.88%, juice from 36.5–61.3%, **BS** from 5.49–30.36%, and **P** from 24.12–53.27% (with **P** accounting for an average of 39.52% of the total fruit weight) [31].

The current study was conducted using pomegranate samples designated as **1**, **2**, and **3**. Respectively, the **P** content in these samples was 29.7%, 23.1%, and 37.6%, with **P**/**BS** (w/w) ratios of 1.58:1, 1.03:1, and 3.77:1.

Maceration of the resulting mixtures was tested using a 1:2 (g/mL) solid-to-liquid ratio. Mixtures **1** and **2** were macerated for 4.5 hours at 63 °C, while mixture **3** was macerated for 2.5 hours at 50–55 °C with the addition of 0.015% Fructozym MA-LG enzyme.

During maceration, a technical challenge arose: the solid components tended to soften and agglomerate, making liquid phase separation difficult. This phenomenon is attributed to the low cellulose content in these pomegranate fractions, particularly within the **P** component [32]. Comparative analysis of various fruit peels shows that air-dried pomegranate peel contains significantly less cellulose (0.50 g/100 g) than the peels of persimmon (11.0 g/100 g), mandarin (4.60 g/100 g), and pear (6.80 g/100 g) at equivalent moisture levels [33]. Higher cellulose concentrations would likely enhance the structural integrity and shape retention of the pomegranate peel fragments.

From the mixtures of **P+BS** samples of garnets 1, 2 and 3, 44.48±0.97%, 50.56±1.14% and 61.16±1.55% of dry substances to their total weight in the bulk of the starting material were released into the solution, respectively.

For the **P+BS** mixtures of pomegranate samples **1**, **2**, and **3**, the release of dry substances into the solution accounted for 44.48 ± 0.97%, 50.56 ± 1.14%, and 61.16 ± 1.55% of the total starting material weight, respectively.

This degree of dry matter extraction from dried peel is not unusual, even when using basic techniques such as atmospheric pressure maceration. Wang et al. [34] reported a total extract yield of 43% by weight using aqueous maceration on dried peel.

The dry substance yield from pomegranate sample **3** (61.16 ± 1.55%) is comparable to results in a published study [35], in which a two-stage maceration of 6.03 ± 0.03 g of dry peel with 180 mL of water yielded a 60.3% release of dry matter (603 mg/g). Similarly, another study reported a total extract yield of 614 mg/g from completely dried starting material under analogous conditions [36].

Broadly, this opens new possibilities for understanding their dual functionality, as recent studies [37-38] have confirmed the potential of pomegranate peel polyphenols and seed oil as bioactive ingredients for modern topical therapies.

A significant challenge associated with the unsaturated fatty acids in the concentrated pomegranate seed oil extract obtained in this study is their susceptibility to oxidation, which can lead to the development of off-flavors and odors. Consequently, the shelf life and storage stability of the oil are limited by the oxidative propensity of these fatty acids.

Pomegranate seed oil typically requires specialized processing or the addition of stabilizers to inhibit oxidation. For example, efforts to minimize oil oxidation often involve adding antioxidants such as tocopherols at concentrations of 50 to 1000 ppm; however, definitive improvements in the stability of oil obtained through this method have not been widely established [39]. In the present study, this challenge is addressed by the high concentration of polyphenols within the extract, which function as potent natural antioxidants [40-41]. The extract also contains reducing sugars that enhance oxidative stability and reduce the water activity of the oil-containing concentrate. Furthermore, certain simple carbohydrates are known to act as potential hydroxyl radical scavengers [42-43].

Due to the high content of rare oil (to g/100 g in an extract with 57 g dry matter content) and particularly polyphenols (to g/100 g), this concentrate may serve as an analog to the commercial polyphenolic extract POMx (POM Wonderful, USA). In POMx, the concentrations of - and -punicalagin isomers in 26 are 21.80 and 4.79 mg/mL, respectively—which is 26 times higher than the levels found in pomegranate juice (0.15 and 0.02 mg/mL). This elevated concentration also applies to ellagic acid glycosides (19.65 mg/mL in the extract versus 0.33 mg/mL in the juice) and total polyphenols [44].

Analysis of the chemical composition of concentrated **P+BS** extracts from pomegranate samples **1**, **2**, and **3** reveals that they contain not only peel polyphenols and seed oil but also virtually all other constituents of the initial mixtures, including fibers. In this regard, a published study [45] highlights the superior antioxidant effect of pomegranate internal septum extract compared to whole fruit extract, attributing this to a higher concentration of fibrous components (glucans, xylans, and pectin). Furthermore, as pomegranate concentrates contain intensely colored active compounds, research is ongoing to enhance their color stability during storage [46].

Due to significant differences in the concentrations of primary constituents (polyphenols in the peel and oil in the seeds) [47], **P** and **BS** are typically processed separately. However, these selective processes result in substantial waste in the form of extracted peel and defatted seeds. While the **BS** solid residue is rich in protein and fibers, offering potential nutritional benefits, the protein content in the **P** solid residue is several times lower, rendering it less valuable as a protein source.

In this study, joint maceration of the peel and seeds was performed to partially address this issue, as confirmed by the analysis of powders obtained from drying and grinding the post-extraction residues.

A straightforward solution was identified, involving the sifting of the **P+BS** macerated powder through a 0.5 mm sieve. Consequently, the bulk of the protein was concentrated in the fine fraction, while the majority of the fiber remained in the coarser fraction (particle size >0.5 mm), representing a significant finding for material optimization.

Research indicates [48] that pomegranate powders are of particular value as ingredients in dietary flour products.

5 Conclusions

The results of the joint maceration of pomegranate peels and seeds, conducted in accordance with the objectives outlined in the introduction, are summarized as follows:

Integrating the extraction of both pomegranate bio-waste fractions into a single procedure eliminated redundant steps and reduced operational time and costs. This approach yielded a multifunctional extract with high concentrations of both polyphenols and fatty oil.

Another practically significant result of combining these procedures was a notable increase in protein concentration within the dried and crushed post-extraction residue, particularly in its fine fraction.

Furthermore, this study indicates that future research directions should address the limitations identified in thermal maceration.

The first challenge is the difficulty of separating the resulting solutions due to the softening and clumping of fine particles within the mixture.

The second disadvantage concerns the composition of extracts condensed to 57% dry matter; the majority of this content consists of monosaccharides (45.77–61.35%) rather than active ingredients like polyphenols and oils. This high sugar content may limit their application as liquid phytotherapeutic agents.

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