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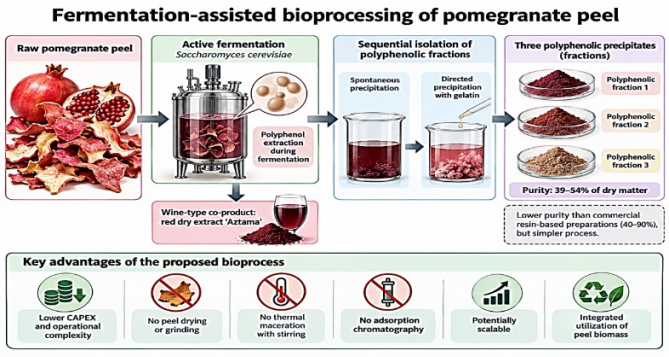
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Pomegranate peel, fermentation without air access, wine extract, self-association of polyphenols, ellagic acid, gelatin-tannate, α-glycosides.

Fermentation - Assisted Valorization of Pomegranate Peel: A Contribution to Resource Efficiency and Circular Bioeconomy

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ABSTRACT: The valorization of pomegranate peel is constrained by the cost and complexity of conventional extraction and purification technologies. The present study proposes a fermentation-assisted process designed to recover polyphenolic fractions from coarse pomegranate peel while simultaneously generating a wine-type co-product and a residual dietary-fiber fraction. The process comprises two principal stages: (i) extraction during anaerobic alcoholic fermentation mediated by Saccharomyces cerevisiae and (ii) sequential fractionation of the resulting hydro-ethanolic extract through spontaneous sedimentation and gelatin-induced precipitation. Three polyphenol-rich precipitates were obtained during clarification, while the remaining liquid phase was retained as a dry red wine-type product designated "Aztanna". Under the selected conditions, coarse peel was fermented for 14 days at 18–22 °C at a peel-to-water ratio of 1:1.5–1.6, with 18% added sucrose and S. cerevisiae. For sample 1, the selected conditions yielded 66.63% recovery of total polyphenols into the liquid extract; for sample 3, the corresponding recovery was 76.74%. During maturation of the extract from sample 3, the insoluble polyphenolic fraction increased from 12.22% after 3 days to 26.00% after 90 days. In a 100-kg peel scenario, the process was calculated to yield approximately 670 g ellagic-acid-rich fraction, 150 g gelatin-tannate, 425 g α-glycosides, and 154.4 L of clarified wine-type extract, in addition to a dietary-fiber residue. The principal technological advantage of the proposed approach is the elimination of several energy- and equipment-intensive operations used in conventional workflows, including drying and fine grinding of the raw peel, thermal maceration, and adsorption chromatography. The results support further pilot-scale evaluation of the process as an integrated valorization route for pomegranate-processing by-products.
ABSTRACT:



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1. INTRODUCTION

Pomegranate (Punica granatum L.) processing generates substantial quantities of peel and seed residues. Because the peel may represent approximately 50–60% of fruit mass, pomegranate processing can generate large volumes of organic by-products [1]. These materials are increasingly viewed not as waste but as sources of compounds with potential technological and economic value, particularly polyphenols, tannins, dietary fiber, and other phytochemicals [2–7].

Pomegranate peel is characterized by a high content of hydrolyzable tannins, among which punicalagins are particularly prominent. Punicalagin occurs as α- and β-isomers and, together with punicalin, can undergo hydrolysis to yield ellagic acid [8, 9]. The concentrations of these compounds vary considerably among cultivars; for example, punicalagin levels of 181–255 mg/g have been reported for the peels of six Spanish cultivars [10]. Other tannins identified in the peel include pedunculagin, granatin A and B, corilagin, tellimagrandin, and gallagylhexoside [11].

In addition to tannins, the peel contains phenolic acids such as gallic, ellagic, vanillic, caffeic, ferulic, cinnamic, chlorogenic, and p-coumaric acids, as well as flavonoids including kaempferol, luteolin, rutin, quercetin, and hesperidin. Triterpenoids and phenylethyl alcohol derivatives have also been reported [12]. The quantitative composition is strongly influenced by cultivar and analytical method [11,13–16]. Pomegranate peel polyphenols have been investigated for antioxidant, antimicrobial, anti-inflammatory, and other biological activities [17–24].

Despite this chemical richness, industrial valorization of pomegranate peel remains challenging. Conventional extraction schemes commonly involve drying, mechanical size reduction, thermal maceration, clarification, concentration, and adsorption-based purification. These operations increase energy consumption, capital requirements, and process complexity and may also promote the formation of viscous colloidal phases that complicate solid–liquid separation [25–28]. Thermal and oxidative exposure can additionally compromise sensitive phytochemicals.

An alternative strategy is therefore to exploit the fresh or minimally processed peel directly and to combine extraction with biological conversion. In the present study, Saccharomyces cerevisiae was used to ferment soluble sugars released from the peel. The resulting ethanol was expected to contribute to a hydro-ethanolic extraction medium while simultaneous sugar consumption reduced the concentration of readily fermentable substrates in the liquid phase. The process was designed to preserve the coarse structure of the peel, thereby facilitating subsequent separation and enabling the residual solid to be further valorized.

The objective of this work was to develop and assess a low-complexity, fermentation-assisted process for the recovery and fractionation of pomegranate peel polyphenols. Particular emphasis was placed on the influence of the peel-to-water ratio (hydromodule), the recovery of polyphenols into the liquid phase, the temporal development of precipitates during maturation, and the potential integration of several co-products within a single processing scheme.

2. MATERIALS AND METHODS

2.1. Experimental substrate

The experimental substrate consisted of the exocarp obtained by manually peeling three intensely pigmented pomegranate samples (Punica granatum L.). The fruits were purchased in late October from the central market in Quba, Azerbaijan. The peel was used in coarse pieces rather than as a finely milled powder.

2.2. Auxiliary materials

Granulated sucrose was used as an additional carbon source in accordance with GOST 33222-2015. The fermentation organism was the commercial wine-yeast preparation Gervin GV1 (associated with Fermivin 7013), consisting of Saccharomyces cerevisiae. Food-grade gelatin, compliant with GOST 11293-2017, was used for selective precipitation of tannin-rich fractions. Water used for preparation of the fermentation medium was purified by reverse osmosis (Thomas Compact system).

2.3. Fermentation-assisted extraction

Conventional extraction of plant materials often relies on comminution, heating, and agitation to increase mass transfer. In pomegranate peel, however, intensive thermal and mechanical treatment can promote hydrolysis of the pectin-rich matrix and

the formation of viscous colloidal material, thereby complicating filtration and phase separation [25, 26]. The present process therefore used coarse peel at ambient temperature to minimize these effects while reducing energy demand.

The peel was fermented anaerobically in glass vessels fitted with hydraulic air locks. Experiments were performed at room temperature, with peel-to-water ratios ranging from 1:1 to 1:10 (g/mL) and fermentation periods of one or two weeks. Six primary extract samples were prepared for each peel sample. Fermentation progress was monitored qualitatively from CO_2 evolution and foam formation. Subsequent optimization experiments were conducted at 18–22 °C with 0.13% S. cerevisiae and 18% sucrose relative to the fermentation mixture.

2.4. Separation and fractionation

Following fermentation, the liquid phase was separated from the coarse peel by decantation and pressing of the residual solids. The recovered liquids were combined and filtered to remove coarse particles. The clarified hydro-ethanolic extract was then allowed to mature at room temperature. Sequential precipitation was used to separate distinct polyphenolic fractions according to their differential solubility and interactions with the fermentation matrix. The first precipitate was collected after approximately 3 days. A 5% gelatin solution was subsequently added to the remaining extract, and the resulting precipitate was recovered after a further 3 days. The remaining extract was maintained for approximately 3 months, after which the final fraction and the clarified liquid product were collected.

2.5. Analytical methods

- Dry matter was determined by drying to constant mass according to GOST 33977-2016.
- Total soluble solids were determined refractometrically in accordance with GOST 28562-90.
- Reducing sugars were determined by the Bertrand method (GOST 8756.13-87).
- Titratable acidity was determined by titration with 0.1 N NaOH and expressed as citric acid equivalents in accordance with ISO 750:2013.
- Ascorbic acid was determined by iodometric titration according to GOST 24556-89.
- pH was measured potentiometrically according to GOST 26188-2016.
- Total polyphenols were determined by permanganatometric titration according to GOST 24027.2-80. The procedure involved determination of total oxidizable substances followed by activated-charcoal treatment and repeat titration; the difference in potassium permanganate consumption was used to estimate the polyphenolic fraction.
- Crude protein was determined by the Kjeldahl method using a nitrogen-to-protein conversion factor of 6.25.
- Dietary fiber was determined by the enzymatic–gravimetric method according to GOST 34844-2002.

2.6. Statistical analysis

The experimental trials were performed using a randomized design. Linear, quadratic, and interaction effects of the independent variables were evaluated at a 95% confidence level ($p < 0.05$). Statistical analysis was carried out using Statgraphics Centurion XV, version 15.1.02 (StatPoint Technologies, Inc., Warrenton, VA, USA).

3. PROCESS RATIONALE AND THEORETICAL CONSIDERATIONS

The proposed process combines biological conversion and solvent generation in a single operation. During alcoholic fermentation, S. cerevisiae converts soluble sugars into ethanol and CO_2. Because sugars diffuse from the peel into the liquid phase while fermentation is occurring, their continuous consumption alters the composition of the extracting medium. The ethanol generated in situ contributes to the hydro-ethanolic solvent environment and may facilitate the transfer and stabilization of selected polyphenolic compounds.

The subsequent fractionation step was designed around the different physicochemical properties of the extracted compounds. Ellagic acid, which has low aqueous solubility, was expected to preferentially form a precipitate during maturation. Tannin-rich compounds, including ellagitannins, were expected to interact strongly with gelatin and precipitate as protein–polyphenol complexes. More soluble glycosylated flavonoids were expected to remain in the clarified liquid for a longer period. The

resulting process therefore links extraction, maturation, and fractionation without requiring a dedicated chromatographic separation step.

It was assumed that this approach would simplify the extraction and separation of polyphenols, expand the product range and ensure high purity of the product. It will allow the integrated use of pomegranate peel biomass in an environmentally sustainable manner, maximizing added value while minimizing resource costs. These improvements will collectively increase the overall cost-effectiveness of the proposed technology, thus aligning with the primary objectives of this study.

Theoretical calculations indicated that such a processing strategy would preserve the anatomical integrity of the coarse-grained pomegranate peel to produce multiple streams with high added value with minimal energy and chemical consumption. The preservation of large fragments of the peel facilitates the subsequent separation of solid and liquid substances and reduces filtration resistance during fermentation at room temperature by reducing the release of mucous pectins and biocolloids, thereby ensuring effective gravity decanting and pressing, and also promotes the production of a hydroethanol extract in which ellagitannins undergo controlled hydrolysis to form ellagic acid and related derivatives. Consistent natural precipitation and precipitation will allow the separation of ellagic acid aggregates, protein tannate complexes and α-glycoside polyphenols, while clarified tartaric filler liquid (ethanol content 9-14%) will retain flavonoids and phenolic acids of medium and high polarity. And this is a very important aspect, since more intensive methods (ultrasound, pressurized liquids, alkaline hydrolysis, and DES extraction) require special equipment, higher energy, or strong reagents, and often lead to the formation of viscous colloids, which complicates subsequent processing; a method based on cold fermentation should simplify how to obtain both the extract and its separation.

It was expected that such an approach should contribute to achieving the goals of closed-cycle bioeconomics by converting the main by-product of the agro-industrial complex into a range of marketable products, as well as by reducing waste streams and pollutant emissions associated with traditional thermal and acid pretreatment. The solid post - extraction residues can be dried and crushed for use as dietary fibers, antimicrobial powders, or fillers for biodegradable polymer films. While liquid and solid phenolic fractions can be used as raw materials for functional beverages, nutraceuticals, cosmetics (after appropriate solubilization or formulation) and potential active components of packaging.

The main expectations are also related to the fact that the technical solution being developed will be easy to integrate into the existing infrastructure of a winery or juice production, which allows for increased added value without the use of aggressive chemicals or high-temperature pretreatment and complex special equipment.

4. RESULTS AND DISCUSSION

4.1. Chemical composition of the initial peel

The three peel samples differed substantially in composition (Table 1). Peel yield represented 29.70–38.97% of fruit mass. On a fresh-weight basis, water content ranged from 64.00 to 69.70 g/100 g, total polyphenols from 2.60 to 3.60 g/100 g, monosaccharides from 10.08 to 20.89 g/100 g, titratable acidity from 2.68 to 5.69 g/100 g, protein from 1.66 to 2.50 g/100 g, and fat from 0.50 to 1.00 g/100 g. Across the three samples, the mean total polyphenol content was 3.14 ± 0.03 g/100 g fresh weight, while mean fermentable monosaccharides were 14.25 ± 0.12 g/100 g.

Based on the measured concentrations of monosaccharides, sucrose, titratable acids, and polyphenols, the theoretical soluble fraction was estimated at approximately 81.05%, 58.38%, and 52.03% of total dry matter for samples 1, 2, and 3, respectively, with a mean of approximately 64.10%. The authors note that practical recovery may be lower because of incomplete mass transfer and process losses.

Table 1 - Yield and chemical composition of the three pomegranate peel samples.

Parameter	Sample 1	Sample 2	Sample 3	Mean (1–3)
Peel yield (% fruit mass)	32.00±0.64	38.97±0.80	29.70±0.40	33.56±0.80
Water (g/100 g	64.00±1.62	69.70±1.65	64.02±1.70	65.90±1.65

FW)				
Total polyphenols (g/100 g FW)	2.60±0.02	3.22±0.03	3.60±0.04	3.14±0.03
Monosaccharides (g/100 g FW)	20.89±0.10	11.79±0.09	10.08±0.08	14.25±0.12
Sucrose (g/100 g FW)	0.00	0.00	0.66±0.01	0.22±0.01
Titratable acids (g/100 g FW)	5.69±0.04	2.68±0.03	4.39±0.04	4.25±0.03
Ash (g/100 g FW)	0.50±0.01	0.57±0.01	0.75±0.01	0.61±0.01
Protein (N×6.25; g/100 g FW)	2.00±0.02	1.66±0.02	2.50±0.02	2.05±0.02
Fat (g/100 g FW)	0.50±0.01	0.80±0.01	1.00±0.01	0.77±0.01
p-value	≤0,05	≤0,05	≤0,05	≤0,05

4.1.1. Fermentation performance and effect of the hydromodule

To evaluate how changes in the hydromodule affected the quantitative recovery of dry matter and polyphenols, experiments were conducted over a two-week fermentation period for samples (1) and (3) at 18-22° C with the addition of 0.13% S. cerevisiae and 18% granulated sugar. The resulting data are detailed in Table 2.

Table 3 delineates the metabolic utilization of total carbohydrates (including both endogenous sugars and exogenous additions) and proteins during a two-week fermentation of sample (1) at 18-22 °C, utilizing an inoculation of 0.13% S. cerevisiae and the addition of 18% sucrose relative to the total mass of the fermentation mixture.

The acidic composition of the peel generated fermentation media with pH values of approximately 2.8–3.2. Under these conditions, S. cerevisiae was able to ferment the soluble sugars while the low pH was unfavorable to many competing spoilage microorganisms. The natural sugar content of the peel, however, was insufficient to produce the ethanol concentration targeted for the wine-type co-product. Based on the reported sugar concentrations, the theoretical ethanol content from 400 g of peel was estimated at 4.12–8.01% vol., depending on the sample. Additional sucrose was therefore introduced to increase the fermentable-carbon concentration.

The peel-to-water ratio exerted a measurable effect on extraction. Increasing the hydromodule from 1:1 to 1:8 increased the recovery of total dry matter and total polyphenols in both sample 1 and sample 3. For sample 1, polyphenol recovery increased from 63.29 ± 0.59% at 1:1 to 70.63 ± 0.66% at 1:8. For sample 3, the corresponding increase was from 69.00 ± 0.65% to 74.00 ± 0.72%.

Table 2 - Effect of hydromodule on recovery of dry matter and total polyphenols after two weeks of fermentation.

Peel: water (g/mL)	Dry-matter recovery, sample 1 (%)	Dry-matter recovery, sample 3 (%)	Polyphenol recovery, sample 1 (%)	Polyphenol recovery, sample 3 (%)
1:1	63.16±1.23	42.50±0.80	63.29±0.59	69.00±0.65
1:1.5	67.22±1.33	45.14±0.88	66.63±0.62	72.22±0.70
1:4	70.58±1.36	47.19±0.91	67.97±0.63	73.10±0.71
1:8	72.60±1.40	48.95±0.94	70.63±0.66	74.00±0.72
p-value	≤0,05	≤0,05	≤0,05	≤0,05

Although the highest extraction values were observed at the largest hydromodule, protein and sugar utilization by the yeast reached their maximum at 1:4 (75.07 ± 1.45% and 88.19 ± 0.86%, respectively) and decreased slightly at 1:8. This behavior is consistent with a dilution effect: excessive water lowers the concentration of fermentable substrates and nitrogenous nutrients and may also reduce the buffering capacity contributed by organic acids.

Table 3 - Effect of hydromodule on protein and sugar utilization during fermentation.

Peel:water (g/mL)	**Protein utilization (%)**	**Sugar utilization (%)**
1:1	70.00±1.40	85.26±0.80
1:1.5	74.00±1.50	86.06±0.82
1:4	75.07±1.45	88.19±0.86
1:8	74.00±1.48	87.00±0.83
p-value	≤0,05	≤0,05

For subsequent processing, a compromise hydromodule of 1:1.5–1.6 was selected. At this ratio, approximately 168.8 mL of extract was recovered per 100 g of peel on average, while the quantity of water was sufficient to submerge 400 g of coarse peel in the fermentation vessel. Because endogenous sugars were insufficient to achieve the desired ethanol concentration, 72 g sucrose was added per 400 g of peel.

4.1.2. Separation of the fermentation mixture and polyphenol distribution

The preservation of peel structure facilitated decantation and mechanical pressing after fermentation. This was important because the study targeted not only extraction yield but also subsequent phase separation. The authors specifically focused on the free, solvent-accessible phenolic fraction rather than attempting to release all matrix-bound phenolics through hydrolysis.

For sample 1 processed at a 1:1.5 hydromodule, 18–22 °C, 0.13% S. cerevisiae, and 18% added sucrose, approximately 700 mL of wine-type extract was obtained from 400 g of peel. With a total polyphenol concentration of 0.99 ± 0.01 g/100 mL, the extract contained approximately 6.93 g of polyphenols, corresponding to 66.63% of the initial polyphenol mass in the substrate. The freshly pressed solid residue retained approximately 3.46 g, corresponding to 33.37%.

The chemical composition of the primary extract and the solid residue from fermentation of the peel sample 1 (hydromodule 1:1,5; temperature 18-22 °C; concentration of the enzyme in the extraction medium 0.13%, exogenous sucrose - 18%) is given in Table 4.

Table 4 - Chemical composition of the wine-type extract and freshly pressed residue from peel sample 1.

Parameter	Wine extract	Freshly pressed solid residue
Dry substances (g/100 g)	-	11.87±0.13
Soluble dry solids (°Brix)	10.70±0.10	-
Total polyphenols (g/100 mL or g/100 g)	0.99±0.01	1.34±0.01
Monosaccharides	1.18±0.02	1.57±0.02
Sucrose	0.36±0.01	0.52±0.01
Titratable acidity (citric acid)	2.81±0.02	2.81±0.03
Ascorbic acid (mg/100 g)	3.17±0.03	3.34±0.04
Protein (g/100 g)	-	0.80±0.01
Ash (g/100 g)	0.37±0.01	-
Ethanol (% vol.)	14.00±0.12	-
p-value	≤0,05	≤0,05

4.1.3. Maturation and sequential precipitation

During maturation of the hydro-ethanolic extract, the first precipitate formed within approximately 3 days and was described as being predominantly ellagic acid-rich. The remaining polyphenolic material aggregated more gradually over the subsequent 3 months. For sample 3, the insoluble fraction increased from 12.22 ± 0.24% of the initial extract polyphenol mass after 3 days to 26.00 ± 0.49% after 90 days, while the soluble fraction declined from 87.78 ± 1.70% to 74.00 ± 1.38%.

Table 5 illustrates the temporal shift in the ratio between soluble and insoluble polyphenols during the sedimentation of the wine-type extract derived from sample (3). These experimental conditions utilized a 1:1.6 hydromodule at 18-22 °C, concentration of the enzyme in the extraction medium 0.13%, exogenous sucrose - 18%.

Table 5 - Change in soluble and insoluble polyphenolic fractions during maturation of the extract from sample 3.

Maturation time (days)	Insoluble polyphenols (% of initial extract)	Soluble polyphenols (% of initial extract)
3	12.22±0.24	87.78±1.70
30	18.33±0.36	81.67±1.63
90	26.00±0.49	74.00±1.38
p-value	≤0,05	≤0,05

For sample 3, 650 mL of extract containing 1.70 g/100 mL of total polyphenols corresponded to approximately 11.05 g of polyphenols, or 76.74% of the polyphenol mass originally present in 400 g of peel. After 90 days, approximately 19.93% of the initial polyphenol mass was estimated to be represented by the insoluble fraction recovered from the extract.

The reported recovery is lower than that achieved by some highly intensified extraction methods. For comparison, ultrasound-assisted alkaline hydrolysis has produced 59 ± 3 mg punicalagin and 1457 ± 71 mg ellagic acid per 100 g dry peel

[30]. Mechanochemical extraction has yielded 258.09 ± 1.35 mg GAE/g dry extract [31], while pressurized liquid extraction has produced 164.3 ± 10.7 mg total phenolics/g dry matter and 17 ± 3.6 mg punicalagin/g dry matter under optimized conditions [32]. Ultrasound-assisted extraction with 50% methanol has yielded 72.21 mg/g total polyphenols [33]. These comparisons indicate that the present process is not necessarily intended to maximize total phenolic recovery, but rather to balance recovery with reduced processing intensity, simpler separation, and integrated co-product generation.

4.2. Potential products and valorization pathways

The proposed process generates several product streams rather than a single purified extract. The principal liquid product is a clarified, wine-type extract containing the pigments, acids, residual soluble polyphenols, and ethanol generated during fermentation. The authors designate this product "Aztanna". The solid fraction remaining after clarification is further processed as a dietary-fiber material. This multi-product configuration is consistent with the principle that integrated valorization can improve the economics of low-value or low-productivity biomass streams [42].

The literature cited in the original manuscript identifies ellagic acid, tannin-rich preparations, and pomegranate-peel fiber as commercially relevant product classes. Reported applications include food ingredients, cosmetic preparations, nutraceutical products, and functional-fiber materials. These market analogues are presented in the source manuscript primarily to illustrate potential product value rather than to establish clinical efficacy.

4.3. Main technological features of the proposed process

Coarse pomegranate peel from fresh or aged fruit is combined with purified water and granulated sugar at a peel:water:sugar ratio of approximately 1:1.5–1.6:0.18 (w/w).

The mixture is fermented anaerobically with Saccharomyces cerevisiae for approximately 14 days at 18–22 °C.

The liquid phase is recovered by decantation, while the residual peel is mechanically pressed to recover entrained extract. The two liquid fractions are combined and filtered.

The combined extract is matured for approximately 2.5–3 months, during which sequential natural and gelatin-induced precipitation is used to recover polyphenol-rich fractions.

The remaining clarified liquid is retained as the wine-type co-product, while the final insoluble peel residue is dried and milled as a dietary-fiber material.

The sequence is intended to transform a single biomass residue into several partially separated products while using equipment and unit operations already common to fermentation-based fruit processing.

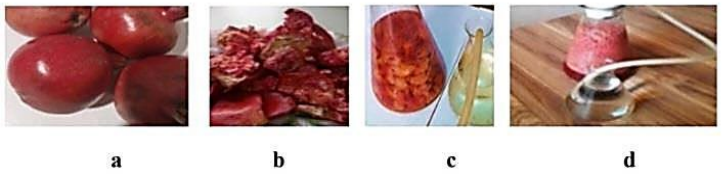


Figure 1- Fermentation-assisted processing of pomegranate peel: (a) fruit; (b) manually separated peel; (c) peel and sugar in a vessel fitted with a water seal; (d) alcoholic fermentation.

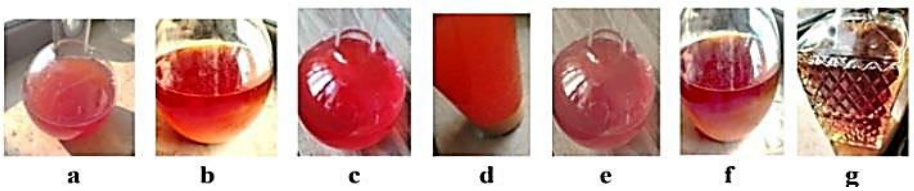


Figure 2- Sequential clarification and precipitation of the wine-type extract: stage 1 - initial wine-type extract (a), after 3 days of exposure (b) and after removal of sediment on the filter (c); Stage 2 - extract residue from stage 1 after treatment with 5% gelatin solution (d), and after removing the sediment on the filter (e); stage 3 - the remainder of the extract from the 2nd stage after exposure to complete clarification (f) and after removing the sediment on the filter (g).

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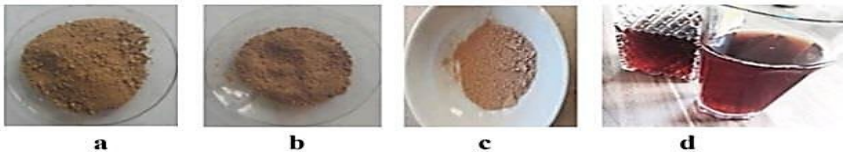


Figure 3 - Recovered polyphenol-rich fractions and clarified wine-type product: (a) ellagic-acid-rich fraction; (b) gelatin-tannate; (c) α-glycosides; (d) Aztanna dry red wine-type product.



Figure 4- Intermediate and final products obtained from the insoluble peel residue: (a) peel residue is raw, (b) after drying and (c) after drying and grinding.

Figure 1-4 shows the photos (visual algorithms) that sequentially display the stages of the new technology.

4.4. Comparison with previously reported fermentation-based approaches

Previous studies have used pomegranate peel primarily as a substrate for bioethanol production, often following extensive pretreatment. One reported approach employed drying, grinding, hydrolysis with 5% HNO_3 at 100 °C for 30 min, detoxification with activated carbon, and subsequent fermentation. Another used 3% HNO_3 at 75 °C for 1 h before fermentation [43,44]. Reported ethanol yields were 0.42 ± 0.08 and 0.43 ± 0.04–0.41 ± 0.03 g/g reducing sugars, depending on the organism and process conditions.

Another approach combined hydrothermal pretreatment, enzymatic saccharification, and fermentation with S. cerevisiae. Under the reported optimized conditions, 90.4% of the initial sugar was consumed and the maximum ethanol concentration reached 12.9 g/L [45]. Although this strategy avoids nitric acid, the hydrothermal pretreatment may remove soluble sugars, pectin, phenolic compounds, and other components that could otherwise contribute to the integrated valorization of the peel.

A further study investigated steam treatment followed by anaerobic fermentation and reported a marked reduction in the molecular weight of peel oligo- and polysaccharides, together with increased tannin concentration in the resulting extract [46]. The reported dry-extract yield ranged from 28% to 50% of dry peel mass. The present study differs in its objective: rather than maximizing hydrolysis or ethanol production, it seeks to preserve the coarse structure of the peel and recover a free polyphenolic fraction while simultaneously generating multiple co-products.

4.5. Separation strategies for pomegranate-peel polyphenols

Three broad approaches to the separation of pomegranate-peel polyphenols are represented in the cited literature: spontaneous sedimentation, induced precipitation, and adsorption-based purification. Each offers a different balance of selectivity, cost, equipment requirements, and product purity [47–60].

4.5.1. Spontaneous precipitation

Natural clarification during storage can result from self-association of polyphenols, hydrolysis of tannins to poorly soluble products such as ellagic acid, interactions between tannins and residual proteins, and temperature-dependent changes in solubility. In the present process, these mechanisms are used deliberately by extending the maturation period and collecting sediment at defined stages.

4.5.2. Gelatin-induced precipitation

Gelatin is a conventional protein-based fining agent for tannin-rich extracts. Its interaction with polyphenols is attributed primarily to hydrogen bonding and hydrophobic interactions, which promote formation of larger, insoluble aggregates. The efficiency of the process may depend on gelatin preparation, pH, temperature, and protein concentration. The source manuscript notes that excessive gelatin can stabilize colloidal material rather than promote sedimentation [50].

The main mechanisms of directional deposition are presented in Table 6.

Table 6 - Selected mechanisms used for directional precipitation of polyphenolic compounds.

Method	Principal mechanism
pH adjustment	Changes in acidity alter the solubility of selected phenolic fractions and may induce precipitation.
Protein precipitation	Gelatin, casein, or albumin forms insoluble complexes with tannins.
Alcohol precipitation	Ethanol concentration can alter the solubility of polysaccharides and polyphenolic complexes.
Salting-out	Salts reduce the solubility of selected organic compounds.
Metal-ion precipitation	Metal ions can form poorly soluble metal–phenolate complexes.
Synthetic polymers	PVPP can selectively adsorb phenolic compounds in oenological applications.

4.5.3. Adsorption and membrane-based alternatives

Modern purification workflows increasingly employ macroporous adsorption resins, membrane processes, and chromatographic techniques for selective recovery of target compounds such as punicalagin and ellagic acid [53–60]. In a typical resin-based process, dried and milled peel is extracted with water or aqueous ethanol, the extract is filtered and concentrated, polyphenols are adsorbed onto a resin, impurities are washed away, and the target compounds are desorbed with ethanol before final concentration and drying. These methods can produce higher-purity materials but require additional equipment, solvent management, adsorbent regeneration, and energy-intensive drying and concentration steps.

The proposed process accepts lower fraction purity in exchange for reduced unit-operation complexity and simultaneous recovery of several products. The reported polyphenol-rich fractions fall within approximately 32–54% purity depending on the fraction and processing configuration. Accordingly, the process should be viewed as a low-complexity valorization strategy rather than a direct substitute for chromatographic processes intended to manufacture pharmaceutical-grade isolates.

4.6. Technological feasibility and integrated processing scheme

The main technological argument for the proposed process is the reduction of pretreatment requirements. Fresh, coarse peel can be fermented directly at 18–22 °C without prior drying, fine grinding, or thermal maceration. The preservation of particle integrity facilitates decantation and pressing and may reduce the formation of viscous colloids associated with aggressive hydrothermal extraction.

The equipment proposed for implementation is largely derived from conventional fruit and wine processing. The process can therefore be organized around a vinifier, screw press, intermediate liquid receiver, conical-bottom settling tank, and Nutsche-type filter/dryer (figure 5). The use of such established unit operations is intended to minimize the need for a dedicated extraction plant.



Figure 5- Main equipment proposed for implementation: (a) vinifier; (b) screw press; (c) intermediate liquid receiver; (d) settling tank with cleaning system; (e) Nutsche filter.

Storage and bottling of finished wine also requires special containers (tanks) made of food-grade stainless steel with floating lids, equipped with an opening for supplying a small amount of nitrogen to maintain low pressure and completely isolate the wine from oxygen in the air.

Figure 6 presents the complete process scheme for the proposed co-production of polyphenolic fractions and a dry red wine-type extract from pomegranate peel.

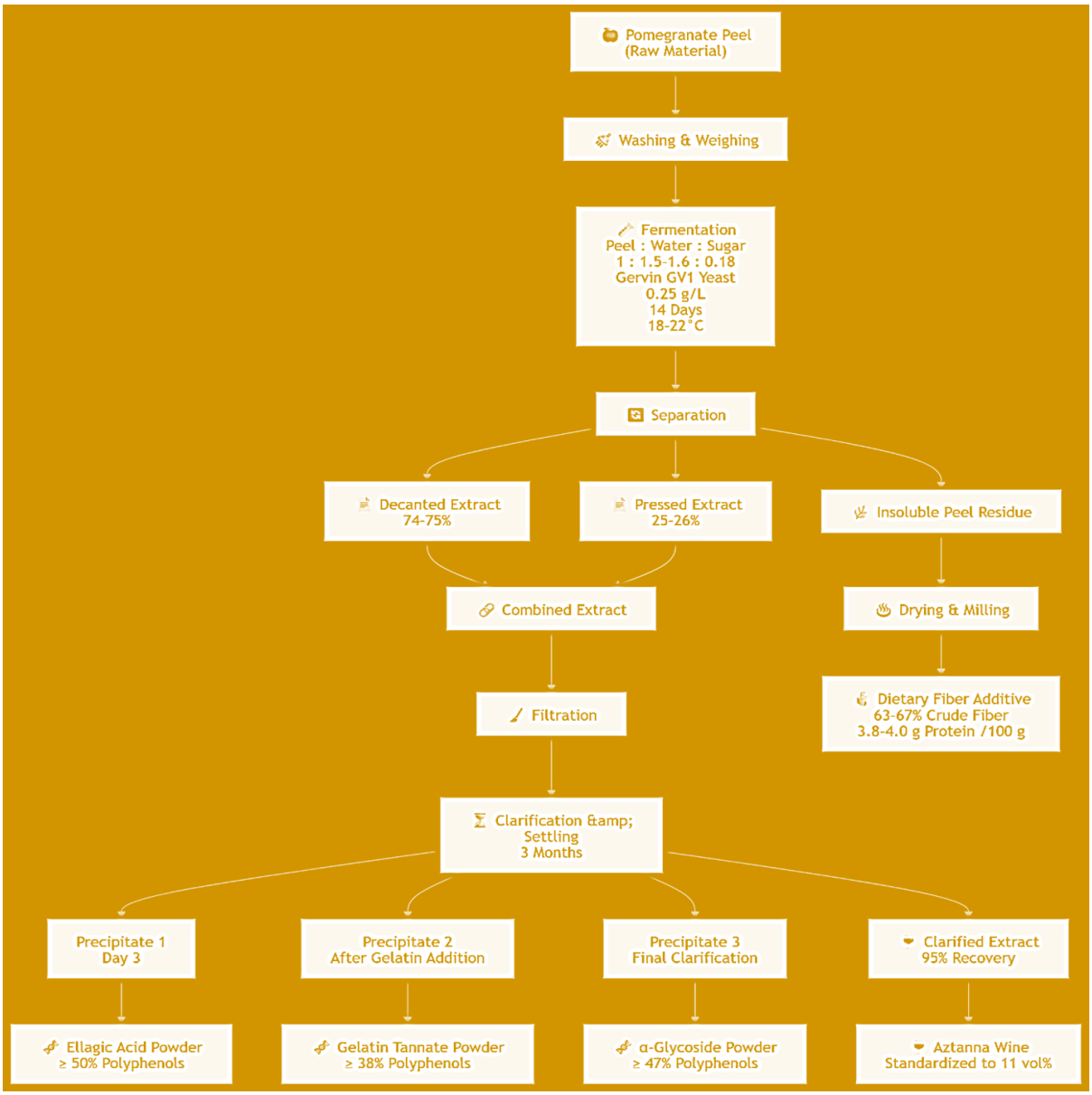


Figure 6 - Overall process scheme for fermentation-assisted extraction and sequential recovery of polyphenolic fractions, wine-type extract, and dietary-fiber residue.

4.7. Example mass balance and commercialization scenario

To illustrate the potential scale of the process, the source manuscript considers 100 kg of sample-3 peel containing 3.60 g polyphenols and 10.74 g sugars per 100 g fresh peel. Under the proposed process, 160 L water, 18 kg sucrose, and 62 g Gervin GV1 are added. After approximately two weeks of fermentation, 120.0 L of liquid is recovered by decantation and 42.5 L by pressing; the combined liquid is then clarified by filtration and maturation.

The reported product yields are approximately 670 g of an ellagic-acid-rich fraction (54.30% polyphenols), 150 g gelatin-tannate (39.49% polyphenols), and 425 g α-glycosides (49.36% polyphenols). The residual clarified liquid volume is reported as 154.4 L with approximately 9% vol. alcohol in the example batch. The residual peel is further processed to produce approximately 16.25 kg of powdered dietary-fiber material.

The original manuscript also provides an illustrative market-value calculation based on assumed manufacturer prices. These calculations are useful as a preliminary economic scenario, but they should not be interpreted as a validated profitability analysis because they do not incorporate full capital depreciation, labor, utilities, waste management, regulatory compliance, quality control, packaging, distribution, or scale-dependent losses. The source estimates a total product value of approximately USD 2,404 per 100 kg of peel and approximately USD 240,000 for 10 tonnes of peel under the stated assumptions.

5. ECONOMIC, ENVIRONMENTAL AND TECHNOLOGICAL ASSESSMENT OF PEEL VALORIZATION

5.1 Techno economic considerations for industrial implementation

5.1.1 Cost structure of conventional versus simplified extraction workflows

Cost drivers in pomegranate peel valorization differ substantially between conventional polyphenol extraction schemes and the simplified fermentation assisted workflow based on coarse exocarp. Conventional industrial technologies are described as relying on energy intensive desiccation, mechanical comminution, and thermal maceration, followed by complex adsorption chromatography on macro-porous resins. These unit operations collectively impose high operational costs and low efficiency, which in turn restrict large scale deployment of peel polyphenol production despite considerable mar-ket demand for bioactive compounds that support human health and environmental resistance. Resin based chromatographic purification represents a particularly cost intensive step. Because the concentration of polyphenols in peel is markedly lower than that of simple sugars and fibers, the mass ratio of pure target substance to initial dry peel can reach 1 : 100 or higher, especially when isolating individual molecules such as punicalagin or ellagic acid. Under such conditions, hundreds of kilograms of resin may be necessary to isolate merely 1 kg of pure polyphenols from 100 kg of processed peel. This low mass efficiency is directly reflected in product pricing; for example, 500 mg of encapsulated pomegranate extract containing 40% punicalagin can cost 47.31 euros, while cosmetic grade ellagic acid extracts at 95% purity are sold for $186.58–$201.48 per kilogram. These economic indicators demonstrate that optimizing parameters within the existing multi stage resin based workflow is unlikely to deliver major cost reductions without more fundamental process simplification. Beyond sorbent usage, conventional schemes incur additional expenses through high temperature processing. Mechanical grinding and thermal maceration of peel increase energy demand and cause hydrolytic breakdown of the pectin rich matrix, converting extraction mixtures into viscous mucilage that severely hinders phase separation and purification. Oxidative and thermal degradation of bioactive compounds during desiccation and heating further reduce process yields, effectively raising the cost per unit of recovered antioxidant. These technical drawbacks contribute to the assessment that conventional workflows are characterized by low efficiency and high operational costs, and they help explain why many juice factories discard peel rather than invest in drying plants and specialized workshops for oil and polyphenol extraction. In contrast, the fermentation assisted extraction strategy replaces several cost intensive operations with ambient temperature processing and widely available wine making equipment. Coarse peel from manual or mechanical cleaning is mixed with water and sugar and fermented for 14 days at 18-22 o C using Saccharomyces cerevisiae, thereby eliminating prior drying, fine grinding, and aggressive hydrothermal pretreatment. The process exploits biosynthetic ethanol as an in situ co solvent, avoiding external solvent purchase and reducing viscosity without mechanical agitation. Subsequent maturation over 2–3 months is used not merely for sensory development but as a low energy clarifi-cation step during which three polyphenol fractions (ellagic acid aggregates, gelatin tannate, and α glycosides) are recovered by natural and induced precipitation. These precipitates are filtered, washed, and dried below 60 o C, yielding fractions with 32-49% purity without chromatographic sorbents. Capital and operating costs in the simplified workflow are structured around standard winery devices rather than specialized chemical reactors or chromatographic systems. A vinifier equipped with temperature control and automatic cap management handles fermentation of must with solids, ensuring continuous contact between peel fragments and liquid. Screw presses transport, dewater, and compact solid residues, while intermediate stainless steel tanks and conical bottom wine containers manage gravity run and pressed liquids under airtight conditions. Nutsche filter dryers integrate filtration, washing, and drying of precipitated polyphenols into a single operation, minimizing handling and labor. All units are built from food grade stainless steel and designed for low power

consumption, aligning the process with existing food production conditions rather than chemical plant infrastructure. Economic analysis linked to this simplified co production framework underscores its impact on cost structure. Direct fermentation of 100 kg peel under the described parameters yields wine valued at approximately $617 and polyphenolic fractions totaling 1.245 kg with a wholesale value near $1787, for combined revenues around $2404. Scaling to 10 tons of raw peel per season generates projected income of roughly $240000. These returns are achieved without investment in high pressure equipment, aggressive acid systems, or large resin inventories, and they are framed as evidence that process simplification, coupled with multi product outputs, can transform peel from costly waste into an economically central feedstock.

5.1.2 Revenue potentials from multi product peel processing chains

This estimate is explicitly designated as preliminary, since a full profitability analysis requires confirmation on a production scale, but low operating and non-production costs imply a high rate of return. The economic conclusion is that comprehensive utilization of peel biomass in this way enhances overall viability, meets the study's stated objective of maximizing value addition, and aligns with the demand for environmentally sustainable processing. The structure of the process itself explains how these revenue streams arise. Coarse peel is mixed with water and sugar in a ratio of 1:1.5-1.6:0.18 and fermented for 14 days with Saccharomyces cerevisiae, producing a wine extract that already possesses the ethanol strength (9-13% vol.) and pigmentation typical of commercial dry red wines. Subsequent maturation for 2.5-3 months yields three discrete polyphenol precipitates through natural and gelatin induced sedimentation: ellagic acid aggregates, gelatin tannate, and α glycosidic polyphenols. These fractions are filtered, washed, dried below 60 o C, and ground to powders with 32-49% purity, while the clarified supernatant is stored as a dry red wine ready for bottling under the trade name AzTanna. Revenue is thus not derived from a single output, but from the simultaneous production of a wine style beverage and several concentrated phenolic ingredients. Price benchmarks from existing markets contextualize the economic significance of these fractions. Cosmetic grade ellagic acid extracts produced by HPLC at 95% purity are sold at $186.58–$201.48 per kilogram, and pharmaceutical grade preparations with 40-95% purity are available at $17.00-$34.50 per 5 g. Gelatin tannate powders and capsules containing 250-500 mg of the complex are marketed for diarrhea treatment at $3.50-$6.20 per pack of 8-10 sachets. In parallel, encapsulated pomegranate extract with 40% punicalagin content can reach 47.31 euros for 500 mg. These price levels demonstrate that peel derived phenolics occupy a high value segment in nutraceutical, cosmetic, and pharmaceutical markets, so even modest quantities of dry fractions from the fermentation process can contribute disproportionately to total revenue. The economic comparison with conventional resin based workflows highlights how a multi-product, simplified scheme reshapes the cost-revenue balance. Traditional extraction with drying, grinding, heated aqueous or hydroalcoholic maceration, and macroporous resin adsorption is characterized by low efficiency and high operating costs. Because the ratio of pure polyphenols to initial dry peel mass can reach 1:100, hundreds of kilograms of resin are required to isolate 1 kg of active substance from 100 kg of feedstock, and the multi stage thermal processing increases energy expenditure. These factors are reflected in the high unit prices of resin derived extracts and indicate that profitability cannot be improved merely by parameter optimization. In response, the co- production framework deliberately replaces high cost sorbent based purification with ambient temperature fermentation and time dependent precipitation, generating several marketable fractions and a wine extract using standard winery equipment. Revenue potentials therefore stem not only from the high value of individual phenolics but also from the elimination of expensive unit operations and the ability to monetize all major components of the peel stream.

5.2 Environmental sustainability and life cycle aspects

5.2.1 Reduction of waste and pollution by peel valorization

Valorization of pomegranate peel directly addresses waste generation and pollution associated with juice processing by transforming what is often discarded into bioactive products. These materials are frequently treated as waste because factories lack cost effective drying plants and extraction workshops, despite the peel being compositionally rich in polyphenols and tannins and thus better described as bioactive by products. Redirecting this stream into fermentation assisted extraction and subsequent fractionation prevents disposal of large volumes of organic matter and mitigates associated environmental impacts. Conventional industrial technologies for peel polyphenols rely on energy intensive des-iccation, mechanical comminution, and thermal maceration, followed by adsorption chromatography on macroporous resins. These workflows are characterized by low efficiency and high operational costs, and they tend to generate viscous colloidal suspensions that

complicate separation. Because the ratio of pure polyphenols to initial dry peel can reach 1 : 100, hundreds of kilograms of resin are required to isolate 1 kg of active substance from 100 kg of peel, which not only consumes materials but increases energy demand for extraction, concentration, and drying. Such schemes, restricted by proprietary patents, place economic and environmental constraints on peel utilization and contribute to the continued practice of discarding peel at juice factories. The fermentation assisted process replaces these high impact operations with ambient temperature handling of coarse exocarp, using Saccharomyces cerevisiae Gervin GV1 at 18-22 o C. Mechanical grinding and thermal macera-tion are avoided, so the pectin rich matrix is not hydrolytically broken down into mucilage and viscous colloids. Structural integrity of the exocarp fragments allows efficient gravitational decantation and pressing, reducing the need for energy intensive mechanical clarification. Continuous bioconversion of monosaccharides into ethanol and CO2 prevents oversaturation with dissolved solids, and biosynthetic ethanol acts as a co solvent that stabilizes polyphenols without external solvent addition. By operating in a naturally acidic pH range of 2.8-3.2, supported by endogenous organic acids, spoilage bacteria are suppressed without chemical preservatives, further decreasing pollution associated with auxiliary inputs. Device selection in this simplified workflow also aligns with pollution reduction. Vini-fiers, screw presses, stainless steel intermediate tanks, conical bottom containers with clean in place systems, and Nutsche filter dryers are standard food grade units designed for low power consumption and closed operation. The screw press, for example, transports and compacts solid residues in a perforated housing, significantly reducing waste volume and moisture content, while its closed stainless steel body minimizes odor dispersion. Nutsche filter dryers integrate filtration, washing, and drying of precipitated polyphenols in a single apparatus, avoiding multiple transfers and potential losses or con-tamination of solids. Using existing winery infrastructure to handle peel streams therefore reduces the need for new heavy chemical equipment and associated environmental footprints. Multi product co production is central to decreasing waste. Fermentation of peel with water and sugar yields a wine extract and, after 2.5-3 months maturation, three solid polyphenol fractions: ellagic acid aggregates, gelatin tannate, and α glycosidic polyphenols. These dry fractions, with 32-49% purity, are retained as ingredients for nutraceutical, cosmetic, or pharmaceutical applications, rather than being discharged as sediment. The clarified wine extract, designated AzTanna, is bottled as a dry red wine style prod-uct, further valorizing the liquid phase. By monetizing both liquid and solid outputs, the process provides economic incentives to avoid peel disposal and sup-ports comprehensive biomass utilization. Evidence indicates that peel powders obtained by direct drying and grinding of solid residues are used to produce teas effective against salmonellosis and dysentery, and as partial flour replacers in bread for weight management, drawing on their fiber and antioxidant content. Such uses extend the value chain beyond extracts and wines, ensuring that even the remaining fibrous matrix is incorporated into food systems rather than entering waste streams. Together, the combination of cold fermentation, oenological fractionation, and downstream powder applications exemplifies a practical route by which peel valorization reduces organic waste generation, limits chemical and energy inputs, and thus attenuates pollution linked to pomegranate processing.

5.2.2 Contribution to resource efficiency and circular bioeconomy

Resource efficiency in pomegranate processing is fundamentally improved when peel is reframed from waste to bioactive feedstock and incorporated into integrated valorization chains. The global production of Punica granatum exceeds 3 million tons, with the exocarp accounting for approximately 50-60% of the fruit's weight; this corresponds to about 1.62 million tons of peel, which would traditionally be considered waste. Given the high content of polyphenols, tannins, and other bioactive components, it is more accurate to describe these streams as bioactive by-products rather than as inert residues, but many enterprises still dispose of them because the logistical and capital requirements for drying and extraction plants are perceived as excessive. Conventional industrial extraction technolo-gies for peel polyphenols are characterized by energy intensive desiccation, mechanical comminution, thermal maceration, and complex adsorption chromatography on macroporous resins. These workflows are described as low in efficiency and high in operational cost, with viscous mucilage formation and fouling of equipment further undermining practicality. Because the concentration of polyphenols in peel is significantly lower than that of simple sugars and fibers, the mass ratio of pure target substance to initial dry peel can reach 1: 100 or higher, so hundreds of kilograms of resin may be required to isolate just 1 kg of polyphenols from 100 kg of processed material. This structural inefficiency is reflected in high market prices for standardized extracts and encapsulated products, and analysis concludes that parameter optimization within such schemes is unlikely to deliver substantial gains in resource efficiency without more fundamental simplification and broader utilization of peel components. The fermentation assisted technology developed for coarse exocarp addresses these limita-tions by replacing high temperature, sorbent intensive steps with ambient

extraction and oenological fractionation, thereby enhancing resource efficiency at both process and product levels. Coarse peel from manual or mechanical cleaning is directly fermented at 18-22 o C with Saccharomyces cerevisiae, using hydromodules of 1: 1.5-1.6 and calibrated sucrose addition to achieve ethanol levels of 9-14% comparable to dry wines. Mechanical grinding, desiccation, and aggressive hydrothermal pretreatment are omitted, which avoids hydrolytic breakdown of the pectin rich matrix into viscous colloids and re-duces energy consumption. Biosynthetic ethanol generated during fermentation acts as an in situ co solvent, stabilizing polyphenols and lowering viscosity without external solvent input. Structural in-tegrity of the exocarp enables high efficiency gravitational decantation and pressing, simplifying solid liquid separation and supporting comprehensive recovery of both liquid and solid fractions. Co - production is central to the circular bioeconomy contribution of this workflow. Rather than targeting a single purified compound, the process yields a portfolio of products from the same peel stream: a clarified wine extract (AzTanna) with dry red wine characteristics, ellagic acid aggregates formed by spontaneous hydrolysis and self-association of punicalagin and punicalin, gelatin tannate precipitates produced by protein mediated complexation of residual ellagitannins, and α glycosidic polyphenols obtained at the final sedimentation stage. These fractions are filtered, washed, and dried below 60 o C to achieve purities of 32-49%, then ground to powders suitable for use in nutraceuticals, cosmetics, and food applications. Powder produced by direct drying and grinding of peel or solid residues is already employed in teas effective against salmonellosis and dysentery, and as a partial flour replacer in bread for weight management, demonstrating that fibrous matrices rich in polyphenols can be functionally reintegrated into food systems rather than discarded. This increase is interpreted as evidence that the technology simplifies the extraction and separation of polyphenols, diversifies the product range and ensures high purity of products, while simultaneously allowing the integrated use of peel biomass at low operating and non-production costs, thereby increasing overall economic viability within the framework of circular bioeconomics. By integrating cold fermentation, time dependent precipitation, and reuse of standard winery equipment, the proposed methodology converts a problematic waste stream into multiple high value outputs, reduces reliance on energy intensive and chemically aggressive operations, and closes material cycles in pomegranate processing. In doing so, it simultaneously addresses waste reduction, resource efficiency, and value addition objectives that are central to circular bioeconomy strategies in agro industrial systems.

4. CONCLUSION

The study presents a fermentation-assisted strategy for the integrated valorization of pomegranate peel. The process combines direct extraction from coarse peel with anaerobic fermentation by Saccharomyces cerevisiae, followed by sequential spontaneous and gelatin-induced precipitation. Under the selected operating conditions, the method recovered a substantial fraction of the peel polyphenols into a hydro-ethanolic extract while preserving a solid residue suitable for further fiber valorization.

The principal technological advantage is the reduction of processing intensity relative to conventional workflows based on drying, fine grinding, thermal extraction, concentration, and adsorption chromatography. The process additionally generates multiple co-products, including an ellagic-acid-rich fraction, gelatin-tannate, an α-glycoside-rich fraction, a wine-type liquid product, and a dietary-fiber residue. The reported results therefore support the feasibility of a multi-product approach to pomegranate-peel valorization.

The present findings should nevertheless be regarded as a basis for further development rather than as final evidence of industrial profitability or product standardization. Pilot-scale trials, detailed mass and energy balances, compound-specific analytical characterization, microbiological validation, reproducibility testing across cultivars, and a complete techno-economic and regulatory assessment are required before commercial implementation.

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Lorem ipsum dolor sit amet, consectetur adipiscing elit. The authors acknowledge the technical assistance provided by the Department of Natural Resources.

AUTHOR CONTRIBUTIONS

Samir Hafizov: Conceptualization, Investigation.

Olga Musina: Data Curation, Formal Analysis.

Gharib Hafizov: Methodology, Laboratory Analysis

Elsevar Farzaliyev Data Curation, Formal Analysis.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ETHICS STATEMENT

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ethical approval was not required for this study.

DATA AVAILABILITY STATEMENT

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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