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Research article

Ultrasound-assisted extraction of bioactive compounds from potato peel: A sustainable approach for tannin recovery

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Abstract

This study investigates the ultrasound-assisted extraction of bioactive compounds, particularly tannins, from potato peel, a widely available agricultural by-product. The optimization of extraction parameters, including solvent type (water, methanol, ethanol, acetone) and extraction time (10 and 15 minutes), was carried out to maximize the yield of phenolic compounds and tannins. The results showed that water was the most effective solvent for both phenolic and tannin extraction, with the highest yields obtained at 15 minutes. Specifically, 219.5 ± 75.4 mg of phenolic compounds and 142.83 ± 9.50 mg of tannins per 100g of dry potato peel were recovered using water. The optimization of these extraction parameters was confirmed through statistical analysis, including ANOVA, which revealed significant effects of both solvent type and extraction time on the extraction efficiency ($P<0.01$). The ultrasound-assisted extraction method proved to be an efficient, sustainable, and cost-effective technique, demonstrating its potential for industrial-scale applications, particularly in the food, pharmaceutical, and cosmetic industries. This study offers a promising approach to valorize potato peel waste, contributing to both waste reduction and the production of valuable bioactive compounds.

Keywords: Agricultural by-products, Industrial applications, Potato peel, Tannin extraction, Ultrasound-assisted extraction, Waste valorization.

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1. Introduction

Potato (*Solanum tuberosum*) is one of the most widely grown and consumed crops globally, with its production being a cornerstone of both the agricultural and food industries. It is a staple food in many countries and plays a crucial role in global food security [1,2]. According to the Food and Agriculture Organization (FAO), over 368 million tons of potatoes were produced worldwide in 2021, making it the fourth most important food crop after rice, wheat, and maize [3]. The leading producers of potatoes are China, India, and the Russia, while countries like Iran also significantly contribute to global production [3]. In Iran, potatoes are cultivated extensively, both for domestic consumption and export, and represent a major agricultural commodity. Despite its high production, the large-scale cultivation of potatoes poses an environmental challenge due to the significant amount of waste generated, particularly in the form of potato peels. These peels, which are discarded after the processing of potatoes into products like chips, fries, and mash, remain largely underutilized in most industries, representing a considerable waste management problem [5].

Potato peel, a by-product of potato processing, is an abundant and inexpensive waste material that is often discarded without proper utilization. However, the accumulation of such waste has become a major environmental concern, particularly as the volume of potato peel waste continues to increase with the growing global demand for processed potato products [6]. In fact, it is estimated that around 10–20% of the total weight of potatoes is discarded as peel during processing [7]. The disposal of potato peel waste poses a significant challenge to the potato processing industry, contributing to environmental pollution, waste accumulation in landfills, and the depletion of valuable resources. Furthermore, potato peel, which is rich in bioactive compounds, could potentially be a valuable resource if its components were properly extracted and utilized [8]. However, current waste management practices do not capitalize on this potential, highlighting the need for sustainable approaches that can reduce waste while also adding value to this by-product [9].

Despite being considered waste, potato peel contains several bioactive compounds with significant functional and industrial applications. One of the most valuable compounds found in potato peel is tannins, a class of polyphenolic compounds known for their antioxidant, antimicrobial, and anti-inflammatory properties [8, 10,11]. Tannins are widely used in various industries, including pharmaceuticals, cosmetics, and food processing, due to their ability to neutralize free radicals, inhibit the growth of pathogens, and offer potential health benefits [12, 13,14]. It is estimated that potato peel contains up to 5–15% of its dry weight as phenolic compounds, including tannins, which could be extracted and utilized for value-added applications [15,16]. The extraction of tannins from potato peel, therefore, offers a sustainable way to address the growing concern of waste disposal while simultaneously producing high-value bioactive compounds that can be used in various industrial sectors [17,18]. This process not only reduces the environmental burden but also creates economic value from what was previously considered waste.

Tannins, as polyphenolic compounds, are known for their numerous health benefits, such as antioxidant, anti-inflammatory, and antimicrobial effects [19,20]. These properties make tannins valuable in the food, pharmaceutical, and cosmetics industries [13,14] Numerous studies have explored various methods for extracting tannins from agricultural residues and plant materials, including leaves, barks, and peels [21,22,23,24,25]. Traditional methods of tannin extraction, such as solvent extraction, maceration, and steam distillation, have been widely used, but these methods often suffer from limitations such as long extraction times, high energy consumption, and the use of toxic solvents [22,26,27]. As a result, there has been growing interest in alternative, more efficient extraction techniques that can overcome these challenges. One such technique is ultrasound-assisted extraction, a method that utilizes high-frequency sound waves to enhance the extraction of bioactive compounds from plant materials.

In recent years, ultrasound-assisted extraction has attracted increasing interest as a green and efficient alternative to traditional methods, particularly for extracting bioactive compounds such as tannins from plant materials [26,27,28,29,30,31,32]. This technique has several advantages over conventional methods, including reduced extraction times, lower energy consumption, and the ability to extract heat-sensitive compounds without causing thermal degradation. In the case of potato peel, ultrasound-assisted extraction has shown potential in enhancing the yield of tannins while minimizing the use of harsh solvents and reducing extraction times [11,34,35]. These findings suggest that further research on optimizing ultrasound-assisted extraction for tannins from potato peel is essential to fully harness its potential and address existing gaps in the literature.

This study was conducted to address the existing gap in the application of ultrasound-assisted extraction for tannin recovery from potato peel, as well as the lack of comprehensive research on optimizing this technique for industrial-scale implementation. The main objective is to explore the feasibility and efficiency of this method in extracting tannins, particularly by optimizing critical parameters such as solvent type, extraction time, and ultrasound intensity. This approach not only addresses the shortcomings of previous studies but also seeks to establish a sustainable and cost-effective method for valorizing potato peel waste. By doing so, this research contributes to closing the existing gap in the field, offering an innovative perspective on waste utilization, and paving the way for the integration of this technique into industrial practices for producing value-added compounds from agricultural by-products.

2. Materials and methods

2.1. Potato peel source and preparation

Fresh potato peel samples were sourced from Shahd Pak Food Industries Company (Tapis), located 20 km from Mashhad on the Mashhad-Quchan road (Fig 1a). The collected peels were washed with distilled water to remove any impurities and air-dried under shaded conditions (Fig 1b) to preserve bioactive compounds. The dried samples were ground into a fine powder using a laboratory grinder (Fig 1c), then sieved through a 40-mesh screen to ensure uniform particle size for subsequent analysis. The experiments were carried out in the chemistry laboratory, Department of Food Science and Engineering, Ferdowsi University of Mashhad.

Fig 1. potato peel Preparation process: a) Fresh potato peel samples before washing; b) Dried potato peel samples; c) Grinding dried potato peel samples using a laboratory grinder

2.2. Chemicals and reagents

The solvents and chemicals used in this study included methanol (98%), ethanol (96%), acetone (99%), deionized water, and the following analytical-grade reagents: Folin-Ciocalteu's phenol reagent, 7.5% (w/v) sodium carbonate solution, polyvinylpolypyrrolidone (PVPP), ferric ammonium sulfate (2%), hydrochloric acid (37%), and butanol (99%). All reagents were purchased from Merck KGaA, (Darmstadt, Germany).

2.3. Ultrasound-assisted extraction process

2.3.1. Equipment and setup

The ultrasonic-assisted extraction was performed using an ultrasonic bath (vCLEAN1-L20 Model, BackerCompany,Iran) operating at a frequency 40 kHz and power400watts. The bath was filled with distilled water, and the sample-containing beakers were placed in a suspended basket to avoid contact with the bath's surface (Fig 2).
The extraction was performed using an ultrasonic cleaner device, model vCLEAN1-L20 from Beker. This device operates at an ultrasonic power of 400 watts and a frequency of 40 kHz. The tank is made of 304 stainless steel with a volume of 20 liters, and the temperature can be adjusted up to 80°C. Additionally, the device features degassing capability and adjustable cleaning time.

Fig 2. Ultrasonic-assisted extraction process with vCLEAN1-L20 Model: Sample-containing beaker suspended in the ultrasonic bath

2.3.2. Extraction procedure

One gram of powdered potato peel was mixed with 10 mL of the selected solvent in a 20-mL beaker. The beakers were sealed to prevent solvent evaporation and placed in the ultrasonic bath for 10 or 15 minutes at 25°C. After extraction, the solution was filtered through Whatman No. 1 filter paper to remove solid residues. The filtrate was centrifuged at 3000 rpm for 10 minutes at 5°C using a Labofuge 200 centrifuge (Labofuge 200 Model, Thermo Fisher Scientific, UK). The supernatant was collected, and preliminary tests confirmed that a second extraction step was unnecessary as it yielded less than 5% additional phenolic compounds [36,37].

2.3.3. Filtration and concentration

The filtered supernatant was stored at 5°C for subsequent analysis. To prevent the degradation of bioactive compounds, the extract was handled under controlled temperature conditions during all stages.

2.3.4. Drying of extract

The extract was dried in a vacuum oven at 45°C for 18 hours under a pressure of approximately 60 mmHg to obtain the dry weight. This method helps to remove residual solvents while preserving the integrity of tannins by minimizing thermal degradation. The dry extract was then weighed, and the tannin content was calculated and reported based on the dry weight.

2.4. Tannin analysis

2.4.1. Qualitative and quantitative determination of tannins

Total Phenolic Content (TPC): The TPC was determined using the Folin-Ciocalteu assay, as described by Mussatto et al. (2011). A 125 µL aliquot of the extract was mixed with 375 µL of Folin-Ciocalteu reagent (diluted 1:10), 1.5 mL of sodium carbonate (7.5% w/v), and 5 mL of deionized water. The mixture was vortexed and incubated in the dark at room temperature for 60 minutes, and absorbance was measured at 765 nm using a UV-Vis spectrophotometer (Unico, USA). Results were expressed as milligrams of gallic acid equivalents (mg GAE) per 100 g of dry potato peel.
Non-Tannin Phenolic Content: PVPP was used to remove tannins from the extract, following [38]. The difference between TPC and non-tannin phenolic content was used to calculate the total tannin content.
Non-tannin phenolic compounds were determined based on the method of Makkar et al. (2001) using PVPP and the Folin–Ciocalteu assay. A mixture of

the extract and PVPP was incubated at 4 °C, centrifuged, and the tannin-free supernatant was collected. The phenolic content of this supernatant was measured using the Folin–Ciocalteu reagent. The non-tannin content was then calculated, and tannin content was determined by subtracting this value from the total phenolic content.

2.4.2. Standard curve preparation

A standard curve was generated using gallic acid solutions with concentrations ranging from 5 to 500 mg/L. Absorbance values at 765 nm were used to establish a linear relationship for calculating TPC and tannin concentrations. [39]

2.4.3. Condensed tannin analysis

Condensed tannins were quantified using the butanol-HCl assay [38]. A 0.5 mL aliquot of the acetone extract was mixed with 3 mL of butanol-HCl reagent and 0.1 mL of ferric ammonium sulfate solution. The mixture was incubated at 97–100°C for 60 minutes in a water bath, cooled to room temperature, and absorbance was measured at 550 nm. Results were expressed as leucocyanidin equivalents per 100 g of dry peel.

2.5. Statistical design

2.5.1. Factorial experimental design

A factorial experimental design was employed to evaluate the effects of solvent type (Methanol, ethanol, acetone, and water) and extraction time (10 and 15 minutes). Data were analyzed using Duncan's multiple range test at a 5% significance level to determine the most effective conditions for maximizing phenolic and tannin recovery.

2.5.2. Statistical analysis

The statistical analysis was conducted using Minitab software. The independent variables were solvent type and extraction time, while the dependent variables were TPC and tannin content. All experiments were performed in quintuplicate, and results were reported as mean ± standard deviation.

3. Results and discussion

3.1. Total phenolic content (TPC)

In this study, the extraction parameters evaluated were the solvent type (methanol, ethanol, acetone, and water) and the extraction time (10 and 15 minutes). The results presented in Table 1 indicate that both solvent type and extraction time have a significant impact on the extraction efficiency.
As observed, water emerged as the most effective solvent for phenolic extraction, especially at 15 minutes of extraction time, yielding 219.5 ± 75.4 mg of phenolic compounds per 100g of dry potato peel. This was significantly higher than other solvents, with methanol (146 ± 93.14 mg/100g) and acetone (65.5 ± 54.5 mg/100g) following in second and third place, respectively. The ethanol extraction at both 10 and 15 minutes resulted in the lowest yields of phenolic compounds (45.5 ± 8.82 mg/100g at 10 minutes and 114.7 ± 75.4 mg/100g at 15 minutes) [40]. The total phenolic content in potato peel powder has been reported to range from 237.7 to 527.2 µg/g dry weight. In another study, phenolic compounds were extracted from pomegranate peel using four different solvents—ethanol, methanol, acetone, and water—and the total phenolic content was found to be 669.35 ± 19.5 mg per 100 g of dry material.[41]

Table 1. Phenolic compounds extracted from ptato peel (mg per 100g Powder).

Solvent	Extraction Time (min)	Mean ± SD (mg/100g)	CV (%)
Water	10	155.96 ± 4.75 **a**	20
	15	219.5 ± 75.4 **b**	10
Methanol	10	78.2 ± 15.30 **c**	19
	15	146 ± 93.14 **d**	4
Ethanol	10	45.5 ± 8.82 **e**	10
	15	114.7 ± 75.4 **f**	8
Acetone	10	48 ± 7.54 **e**	4
	15	65.5 ± 54.5 **f**	2

a, b, c, d, e, f: These letters indicate significant differences between the mean values.

The higher yield of phenolic compounds from water can be attributed to its high polarity, which facilitates the extraction of polar phenolic compounds from potato peel. Water is capable of dissolving a broad spectrum of hydrophilic compounds, which explains its superior performance compared to organic solvents such as methanol, ethanol, and acetone. These findings align with those of [42], who reported that water was the most effective solvent for extracting phenolic compounds from plant materials due to its ability to extract polar substances. Additionally, the extraction time also significantly influenced the phenolic yield. Methanol and water showed higher extraction yields when the extraction time was extended from 10 to 15 minutes. This finding is in agreement with the study by Singh et al. [43], which highlighted the importance of time in the extraction process for increasing the yield of bioactive compounds.

The results of the analysis of variance (ANOVA) for the effect of solvent type and extraction time on the total phenolic content (TPC) of potato peel are shown in Table 2. The analysis indicates that both solvent type ($P<0.01$) and extraction time ($P<0.01$) significantly influence the extraction of phenolic compounds. This means that different solvents and extraction times yield different levels of phenolic compounds from potato peel, with a significant interaction between solvent type and extraction time ($P<0.01$). This suggests that the phenolic extraction efficiency is highly dependent on both the solvent chosen and the duration of extraction.

Table 2. **A**NOVA results for total phenolic content extraction.

Source of Variation	df	Sum of Squares	Mean Squares	F-Value	P-Value	F 5%	F 1%
Treatment	7	16.79195	11.311	34.136	0.000	2.66	4.03
Solvent	3	8.58610	19.536	4.235	0.000	3.24	5.29
Time	1	5.17816	5.17816	69.214	0.000	4.49	8.53
Interaction	3	3.2768	0.922	11.12	0.000	3.24	5.29
Error	16	1.32776	0.082				
Total	23	8.80522					

Note: Significant at 1% level.

The observed differences in solvent efficiency for phenolic extraction are consistent with previous studies. Pizzi noted that tannins and phenolic compounds extracted from fresh plant materials tend to have higher reactivity in complex formation and greater solubility in aqueous solvents compared to their dried counterparts [25]. This suggests that aqueous solvents are more effective in extracting bioactive compounds from fresh plant tissues. Similarly, Ersan found that the extraction yield of phenolic compounds from pistachio skins increased with temperature up to 170°C, although extended exposure to higher temperatures caused a decrease in stability, thereby reducing yields. Additionally [44], Maqsood and Singh emphasized the importance of extraction time, reporting that a longer extraction duration enhances the recovery of phenolic compounds. These findings collectively support the conclusion that both solvent polarity and extraction conditions, such as time and temperature, play critical roles in optimizing the yield of phenolic compounds from plant materials [43,42].

In conclusion, the extraction of phenolic compounds from potato peel is highly dependent on the choice of solvent and the extraction time. Water is the most efficient solvent for phenolic extraction, and the optimal extraction time is 15 minutes. These findings provide valuable insights into the process optimization for industrial applications of ultrasound-assisted extraction of bioactive compounds from potato peel.

3.2. Total tannin content

The results presented in Figure 4 clearly demonstrate that, as observed for the phenolic compounds in the previous section, water is the most efficient solvent for tannin extraction from potato peel among the solvents tested (methanol, ethanol, acetone, and water). The yield obtained with water after 15 minutes of extraction was 142.83 ± 9.50 mg of tannins per 100g of dry potato peel, which was significantly higher than the yields obtained using methanol (62.96 ± 0.63 mg/100g), acetone (14.83 ± 0.14 mg/100g), and ethanol (13.57 ± 3.13 mg/100g). These findings demonstrate that water consistently outperforms other solvents in extracting tannins, as its yield was notably higher across all extraction times. The higher yield observed with water can be attributed to its hydrogen bonding capacity, which facilitates the solvation of tannin molecules. Water, with its ability to form hydrogen bonds, is highly effective at extracting polar compounds such as tannins, which makes it superior to methanol, acetone, and ethanol, solvents with lower polarity and weaker interactions with tannins. These results support the notion that water, with its superior solvent capabilities, is able to extract a broader range of tannin molecules than other organic solvents. This is especially true for tannins, which are highly polar and require a solvent capable of forming strong interactions with them. Additionally, the increase in extraction time from 10 minutes to 15 minutes significantly improved the yield of tannins when water and methanol were used, suggesting that prolonged extraction times allow for more efficient recovery of bioactive compounds.

These findings align with those of Brouwer et al. [45], who, in their review of solvent effects on tannin extraction, highlighted water as the solvent of choice for extracting polar bioactive compounds such as tannins. They noted that the strong hydrogen bonding interactions between water and tannin molecules significantly enhanced the extraction efficiency. Their study confirmed that water consistently provided superior yields in comparison to other solvents, particularly for tannins, which require a solvent capable of forming strong intermolecular interactions due to their highly polar nature. Similarly, Sirisangsawang et al. optimized tannin extraction from coconut coir using water as the solvent and also found that water outperformed ethanol in extracting tannins, especially under conditions of higher temperature (70°C), further reinforcing the notion that water is the optimal solvent for tannin extraction from plant materials. [46]

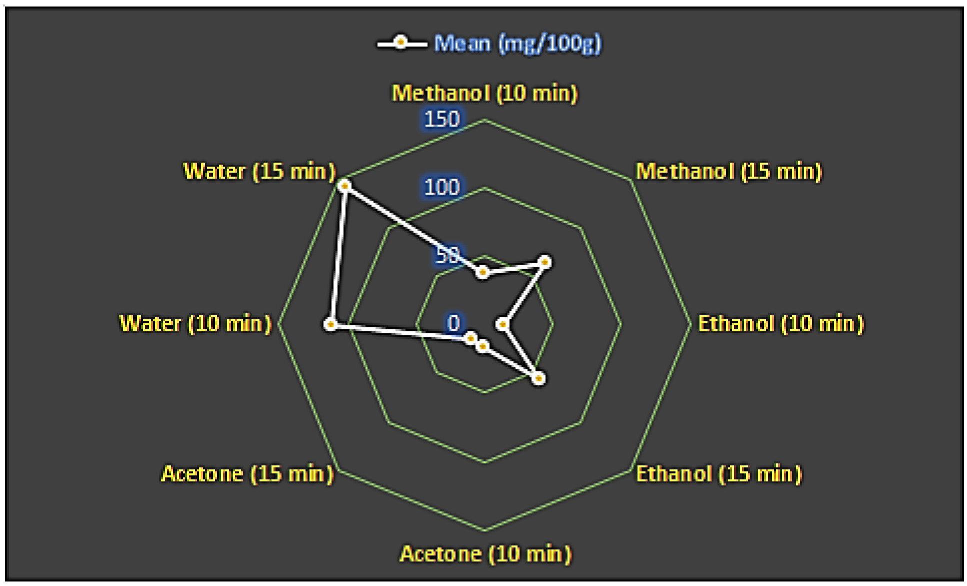

Fig 3. Tannin content extracted from potato peel (mg per 100g dry powder)

The analysis of variance (ANOVA) results, as shown in Table 3, reveal significant effects of both solvent type and extraction time on the total tannin content extracted from potato peel. The data indicate that both factors, solvent type ($P<0.01$) and extraction time ($P<0.01$), have a statistically significant impact on tannin yield at the 1% significance level. This implies that different solvents and extraction times result in varying levels of tannin extraction from potato peel. Additionally, the interaction between solvent type and extraction time ($P<0.01$) was also found to be significant, suggesting that the extraction efficiency is highly dependent on both the solvent chosen and the duration of the extraction process. Specifically, the tannin content increased with longer extraction times, which highlights the importance of optimizing both the solvent type and extraction time for maximizing yield.

Table 3. ANOVA results for total tannin content extraction.

Source of Variation	df	Sum of Squares	Mean Squares	F-Value	P-Value	F 5%	F 1%
Treatment	7	54.48379	36.6911	59.186	0.000	2.66	4.03
Solvent	3	6.43042	5.14347	35.387	0.000	3.24	5.29
Time	1	6.3700	6.3700	9.99	0.000	4.49	8.53
Interaction	3	3.41636	0.54545	14.72	0.000	3.24	5.29

Error	16	5.8592	0.03704
Total	23	12.48972	

Note: Significant at 1% level.

These results are consistent with previous studies in the field. For instance, Cuong et al., in their study on tannin extraction from oak using ultrasound, demonstrated that ultrasound-assisted extraction significantly improves tannin yield. Their analysis, based on ANOVA and Duncan's multiple comparison test, indicated that the extraction efficiency increased with prolonged extraction time [14]. Similarly, the study by Schieber highlighted that ultrasound extraction could enhance the tannin yield from oak and that reducing the extraction time while maintaining efficiency was feasible with this method [47]. Also, the increase in tannin content with longer extraction times is in line with findings from Singh, who noted that the duration of the extraction process is crucial for maximizing the yield of bioactive compounds from plant materials. [43]

3.3. Condensed tannin

The extraction of condensed tannins from potato peel using acetone as a solvent through ultrasound-assisted extraction method was conducted. The results of this extraction, as reported in Figure 5, show the amount of condensed tannins extracted at different times (10 and 15 minutes). Specifically, acetone was found to be effective in extracting condensed tannins from potato peel, with the highest concentration observed at 10 minutes (96.5 mg/100g). At 15 minutes, the concentration slightly decreased to 89.6 mg/100g. These findings indicate that acetone, an organic solvent, is quite effective in extracting condensed tannins from potato peel. While a slight decrease in concentration was observed when the extraction time increased from 10 minutes to 15 minutes, the method still yielded significant amounts of condensed tannins in both cases. This is consistent with the principle that while extended extraction times may sometimes improve yields, they can also lead to a reduction in the concentration of bioactive compounds due to degradation or other factors.

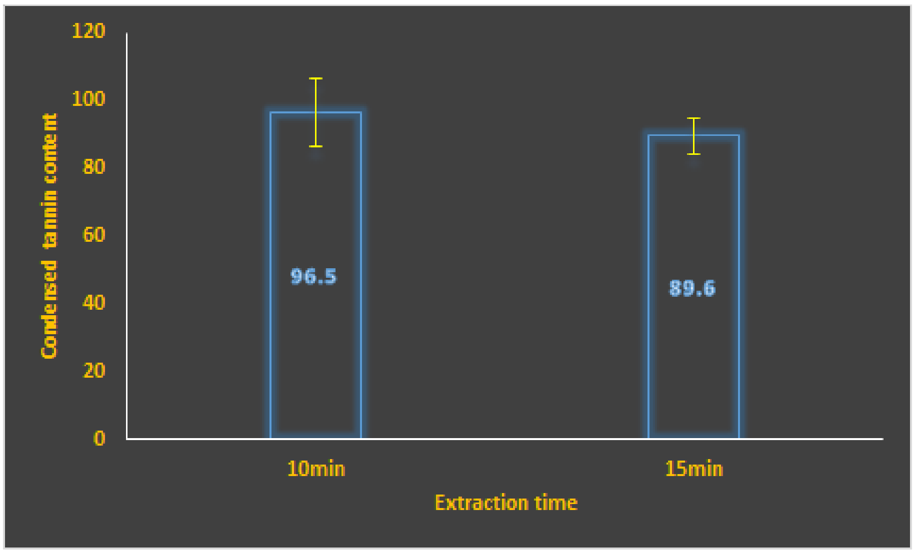

Fig 4. Condensed tannin content extracted from potato peel powder (mg per 100g powder)

Previous studies on different potato varieties have reported a wide range of condensed tannin concentrations. [1] observed that the condensed tannin content in different potato varieties ranged from 22 to 368 mg per 10g of dry potato powder. They highlighted the potential of potatoes as a natural source of anthocyanins, noting that potatoes are a relatively low-cost crop compared to other fruits and vegetables, making them an attractive source of bioactive compounds. Their findings align with our study, where acetone was effective in extracting condensed tannins, although our concentrations were lower than those reported for some potato varieties. Moreover, [48] conducted a study on the stability of anthocyanin content in potatoes, showing no significant changes in anthocyanin levels after 135 days of storage at 4°C. Although their research focused primarily on anthocyanins, the stability of these compounds suggests that condensed tannins in potato peel might also remain stable under similar storage conditions, especially if they are extracted using controlled methods.

The results of the analysis of variance (ANOVA) regarding the effect of extraction time on the amount of condensed tannin extracted from potato peel are presented in Table 4. As shown in this Table, the P-value for the effect of time on the amount of condensed tannin is 0.412, and the F-value is 0.84, indicating that the effect of extraction time on condensed tannin is not significant. This suggests that the variation in the condensed tannin levels observed is likely due to random variation rather than the effect of extraction time.

Table 4. ANOVA results for condensed tannin content.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value	F 5%	F 1%
Time	1	6.43	6.43	0.84^{ns}	0.412	7.71	21.20
Error	4	30.77	7.68				
Total	5	37.15					

ns: Not Significant

Furthermore, post-hoc comparison of means using Duncan's test revealed no significant difference between the 10-minute and 15-minute extraction times for the acetone solvent. This result indicates that increasing the extraction time from 10 to 15 minutes does not significantly affect the condensed tannin content extracted from the potato peel. It is worth noting that in other similar studies, increasing extraction time typically results in higher extraction yields of hydrolyzable tannins. For instance, in studies using similar solvents, it has been observed that hydrolyzable tannins are more efficiently extracted with longer extraction times [43,49]. However, in this study, contrary to expectations, no significant change in condensed tannin levels was observed with increased extraction time. This discrepancy may be due to differences in the chemical composition of the potato peel or the specific effects of the solvent and extraction method used.

3.4. Feasibility and sustainability of ultrasound-assisted extraction for industrial applications

The feasibility and sustainability of ultrasound-assisted extraction for industrial applications, particularly for the extraction of bioactive compounds such as tannins and phenolics from agricultural by-products like potato peel, depend on several factors, including extraction efficiency, environmental impact, scalability, and cost-effectiveness. Based on the findings of this study, the ultrasound-assisted extraction method proves to be an effective, efficient, and environmentally friendly technique for recovering valuable phytochemicals from potato peel, making it a promising approach for industrial applications.

Efficiency and yield: Ultrasound-assisted extraction significantly enhanced the yield of bioactive compounds such as phenolic compounds and tannins from potato peel, as demonstrated by the higher extraction efficiency observed with water as a solvent. The results showed that water, especially when used at an extraction time of 15 minutes, was the most efficient solvent for phenolic compounds and tannins. This is crucial in industrial applications where maximizing yield while minimizing waste is essential for the profitability and sustainability of the process. Moreover, the use of ultrasound energy further improved the extraction efficiency compared to traditional extraction methods by facilitating solvent penetration into the plant matrix and reducing extraction time, which is a major advantage in large-scale industrial settings.

Sustainability: One of the most significant advantages of ultrasound-assisted extraction lies in its sustainability. This method requires lower solvent volumes, reducing the overall consumption of chemicals and, by extension, minimizing the environmental footprint associated with solvent disposal. Water, the most effective solvent in this study, is a non-toxic and environmentally benign solvent, further enhancing the sustainability of the extraction process. Additionally, the reduction in extraction time achieved with ultrasound means lower energy consumption per batch, which contributes to the overall energy efficiency of the process. These features make ultrasound-assisted extraction a green technology suitable for environmentally conscious industries.

Cost-effectiveness: In terms of cost-effectiveness, ultrasound-assisted extraction offers several advantages for large-scale applications. Although the initial setup cost for ultrasound equipment might be higher compared to conventional methods, the reduction in extraction time and the increased yield can significantly lower operational costs in the long run. The ability to extract high-quality bioactive compounds in a shorter period with reduced solvent usage translates into savings in both energy and material costs. Moreover, as agricultural by-products like potato peel are often available at low cost or even as waste products, the use of ultrasound-assisted extraction to extract valuable bioactive compounds can offer a profitable avenue for value addition, particularly in industries such as food, pharmaceuticals, and cosmetics.

Scalability and industrial integration: Ultrasound-assisted extraction has demonstrated significant potential for scalability in industrial applications. The flexibility of the ultrasound-assisted extraction process allows it to be adapted to different plant materials and extraction scales. By optimizing key parameters such as solvent type, extraction time, and power intensity, the process can be tailored to meet the needs of various industries, from small-scale operations to large-scale commercial production. Additionally, the ability to integrate ultrasound-assisted extraction with existing extraction systems, such as continuous flow reactors or batch processing units, makes it a highly adaptable technology for diverse industrial settings.

Challenges and future directions: Despite its advantages, there are some challenges associated with the industrial application of ultrasound-assisted extraction. These include the initial investment in ultrasound equipment, the need for careful optimization of process parameters to ensure consistency and reproducibility, and the potential for cavitation-induced damage to the bioactive compounds at high intensities or prolonged durations. However, these challenges can be mitigated with careful process design and the development of advanced ultrasound equipment. Future research should focus on optimizing the extraction parameters further, exploring the potential for multi-step extraction processes to maximize yield, and assessing the long-term stability and bioactivity of the extracted compounds during storage and processing.

4. Conclusion

The results of this study clearly demonstrate the feasibility of ultrasound-assisted extraction for efficiently recovering bioactive compounds, particularly tannins and phenolic compounds, from potato peel. Water was identified as the most effective solvent for the extraction of both tannins and phenolic compounds, yielding significantly higher amounts than methanol, ethanol, and acetone. The extraction time of 15 minutes optimized both the yield and quality of the extracted compounds. This study also confirmed the effectiveness of ultrasound-assisted extraction in reducing extraction time and solvent consumption compared to traditional methods, contributing to the sustainability of the process.

The data obtained from the ANOVA analysis strongly support the importance of both solvent choice and extraction time in optimizing the extraction process. These findings are consistent with previous research, which also highlighted the superior solvent capabilities of water in extracting bioactive compounds from plant materials. The efficiency and sustainability of the ultrasound-assisted extraction process suggest its suitability for industrial applications where maximizing yield while minimizing waste and environmental impact is crucial.

The feasibility of scaling up this process for industrial applications is also supported by its low energy consumption, reduced solvent use, and potential for integration into existing industrial extraction systems. However, challenges such as the initial cost of ultrasound equipment and the need for optimization of process parameters for consistency should be addressed in future research. Further studies should explore the potential of multi-step extraction processes to maximize yield and the long-term stability of the extracted compounds. Additionally, assessing the bioactivity and potential health benefits of the extracted tannins and phenolics will be critical for evaluating their commercial applications.

In conclusion, ultrasound-assisted extraction of bioactive compounds from potato peel presents a sustainable, cost-effective, and scalable solution to valorize agricultural by-products, reducing environmental impact and contributing to the development of value-added products in the food, pharmaceutical, and cosmetic industries.

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Author contribution: Rasool Khodabakhshian: Conceptualization, methodology, data analysis, writing—original draft preparation, and securing funding. Fatemeh Mortazavi: Conducting experiments and contributing to the development of experimental. Marzieh Moeenfard: conceptualization, investigation, supervision.

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Data availability: The data that support the findings of this study are available from the corresponding author (Dr. Rasool Khodabakhshian) upon reasonable request.

Declarations

Ethical approval: No ethical clearance is required.

Human and animal rights: We declare that there are no animal studies or human participant involvement in the study.

Conflict of interest: The authors declare no competing interests.

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مقاله پژوهشی

استخراج ترکیبات زیست‌فعال از پوست سیب‌زمینی با کمک امواج فراصوت: رویکردی پایدار برای بازیابی تانن

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چکیده

در این پژوهش، استخراج ترکیبات زیست‌فعال، به‌ویژه تانن‌ها، از پوست سیب‌زمینی ـ که یکی از پسماندهای رایج کشاورزی است ـ با استفاده از روش استخراج با کمک امواج فراصوت مورد بررسی قرار گرفت. به‌منظور افزایش بازده استخراج ترکیبات فنولی و تانن‌ها، بهینه‌سازی پارامترهای استخراج از جمله نوع حلال (آب، متانول، اتانول، استون) و زمان استخراج (۱۰ و ۱۵ دقیقه) انجام شد. نتایج نشان داد که آب مؤثرترین حلال برای استخراج ترکیبات فنولی و تانن‌ها بوده و بیشترین بازده در زمان ۱۵ دقیقه به‌دست آمد. به‌طور مشخص، با استفاده از آب، میزان ۲۱۹,۵ ± ۷۵,۴ میلی‌گرم ترکیبات فنولی و ۱۴۲,۸۳ ± ۹,۵۰ میلی‌گرم تانن به ازای هر ۱۰۰ گرم پوست خشک سیب‌زمینی استخراج شد. بهینه بودن این پارامترهای استخراج از طریق تحلیل آماری از جمله آنالیز واریانس (ANOVA) تأیید شد، به‌طوری‌که اثر نوع حلال و زمان استخراج بر بازده استخراج معنادار بود. (P<0.01) روش استخراج با کمک امواج فراصوت به‌عنوان روشی کارآمد، پایدار و مقرون‌به‌صرفه اثبات شد و پتانسیل بالایی برای کاربردهای صنعتی، به‌ویژه در صنایع غذایی، دارویی و آرایشی دارد. این مطالعه رویکردی امیدبخش برای ارزش‌آفرینی از ضایعات پوست سیب‌زمینی ارائه می‌دهد که به کاهش ضایعات و تولید ترکیبات زیست‌فعال ارزشمند کمک می‌کند.

واژگان کلیدی: **پسماندهای کشاورزی، کاربردهای صنعتی، پوست سیب‌زمینی، استخراج تانن، استخراج با کمک امواج فراصوت، بهره‌وری پسماند**

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