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ORIGINAL ARTICLE

Food Chemistry

Comprehensive analysis of physical, chemical, and phenolic acid properties of powders derived from watermelon (*Crimson Sweet*) by-products

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Abstract

This study investigated the physical, chemical, and phenolic properties of watermelon peel powder (WPP), watermelon rind powder (WRP), and watermelon seed powder (WSP) derived from watermelon (*Crimson sweet*) by-products (WBP). As these by-products are typically discarded as waste, the aim was to enhance their added value and explore their potential as sustainable functional food additives. WSP has the largest particle size among the samples. The highest water holding capacity was observed in WRP (8.89%) and oil holding capacity in WPP (4.09%), while WSP had the lowest (6.69% and 2.06%). WRP exhibited better rehydration and solubility, whereas WSP had lower values. WSP contained higher protein and lipid levels (29.46% and 43.0%), while WPP and WRP had greater dietary fiber (78.55% and 48.66%). In terms of mineral matters, Mg and K were substantially greater in WBP than Fe and Na; furthermore, WRP had more K and Mg than the rest. The total phenolic content was determined to be 2855, 3330, and 4196.5 mg GAE/100 g for the WRP, WSP and WPP, respectively. The antioxidant activity as measured by IC50 values, varied between 44.42 (WPP) and 121.29 mg/mL (WRP). A total of 47 phenolic acids were characterised, with genistein being the most abundant compound identified at 10147.1 μg/kg throughout all three powders. In conclusion, these findings highlight the potential of WBP as a sustainable ingredient for the food industry, offering both high nutritional value and functional properties. By valorizing watermelon by-products, this study contributes to waste reduction and supports the development of eco-friendly, nutrient-rich food formulations.

KEYWORDS
antioxidant activity, bulk density, dietary fiber, phenolics, Powder quality

1 | INTRODUCTION

In recent years, with the change in eating habits, fruit and vegetable consumption has increased. At the same time, 2021 was declared the "International Year of Fruits and Vegetables" by the Food and Agriculture Organisation (FAO) (FAO, 2020). Increasing consumption of fruits and vegetables as part of a healthy diet has led to an increase in agricultural waste and wastage (Gupta et al., 2019; Kringel et al., 2020). Despite their high nutritional value, unused seeds, peels, and root parts of fruits and vegetables account for 30% to 50% of total food waste (Gupta et al., 2019). These parts are removed during processing, causing significant environmental problems as well as loss of valuable nutrients (Mallek- Ayadi et al., 2017). The significance of harnessing these waste materials has become increasingly prominent in contemporary times, as it serves to safeguard the environment and mitigate the depletion of important nutrients (Gupta et al., 2019; Kringel et al., 2020). For this purpose, various agricultural wastes such as white cabbage (Gül et al., 2013), apple pulp (Negi et al., 2021), soy and citrus industry waste (Sethi et al., 2022), grape pomace and grape seed (Acun & Gül, 2014), cauliflower by-products (Tukassar et al., 2023), sugar beet and carrot (Bajraktari et al., 2024) can be used in food production. The utilization of food items as functional ingredients shows promising potential in relation to both environmental health and functional nutrition (Mohan & Shanmugam, 2016).

Watermelon is an annual crop of the *Cucurbitaceae* family, which also includes crops such as pumpkin and melon. Watermelon has basically three cultural groups: Citroides, Lanatus, and Vulgaris, and historical evidence suggests that watermelon cultivation dates back to more than 5,000 years ago in northern Africa (Toupal, 2022). In 2022, approximately 3.5 million tonnes of watermelon were produced in Türkiye, while globally, around 102 million tonnes were produced in 2021 (FAO, 2024; Turkish Statistical Institute, 2023). Türkiye produced a significant quantity of watermelon in 2022, making it the second most cultivated crop globally in the fresh fruit and vegetable sector. The majority of this production, amounting to 610 thousand tonnes, occurred primarily in the Adana province of Türkiye. After China and Iran, Türkiye has the highest watermelon production, and per capita watermelon consumption is 40 kg/year (FAO, 2024; ZMO, 2023).

The watermelon is composed of three main components: the seed, which accounts for 2% of its composition, the rind, which constitutes 30%, and the peel, which makes up the remaining 68% of the fruit (Ahamad et al., 2022; Toupal, 2022). The peel and rind of watermelon, the flesh part of which is popularly consumed, is mostly thrown away or used as animal feed in many countries of the world due to its unappealing flavor. Frequently disregarded, watermelon by-products are significant sources of nutrients and bioactive substances. Therefore, these by-products can significantly contribute to enhancing diet quality and promoting health. Recent research validates the use of watermelon waste as reservoirs of natural compounds. These compounds may be employed in diverse food applications, including functional and nutraceutical products, thus contributing to public health improvement (Meghwar et al., 2024) and making them a valuable resource in food development. Opportunities lie in innovative technologies such as extrusion and encapsulation, which can transform these by-products into functional foods, enhancing their value and promoting sustainability (Hasan et al., 2024).

The analysis of melon fruit peels, specifically canary melon, watermelon, and muskmelon, reveals their potential as a source of dietary fiber, which can be valorized in food products like biscuits (Hussain et al., 2024). In some countries, watermelon rind is used in jam, pickle, or juice production to suppress the undesirable flavor (Feizy et al., 2020). Nasharudin et al. (2024) highlighted the innovative approach to using watermelon waste for bacterial cellulose production, emphasizing its sustainability and potential cost advantages.

In recent years, there has been a growing interest in using the rind component due to its rich nutritional composition. This has led to its incorporation into various food products, such as cakes and cookies, with the aim of improving their dietary fiber content (Adegunwa et al., 2019). Watermelon rind is rich in minor components such as dietary fiber, vitamin C, potassium (Ahamad et al., 2022). It also contains L citrulline, which regulates blood pressure and has an anti-aging effect (Ahamad et al., 2022; Mohan & Shanmugam, 2016). The rind is rich in phenolic compounds, which contribute to its antimicrobial properties and therapeutic benefits (Neglo et al., 2021). The peel of the watermelon contains a significant amount of natural antioxidants and non-essential citrulline. It also contains high levels of minerals such as calcium, magnesium, potassium, and iron (Feizy et al., 2020; Ho & Che Dahri, 2016). The peel part has analgesic properties, whereas the rind part shows a vasodilatory effect (Neglo et al., 2021).

Watermelon seeds have a protein content ranging from 25% to 30% and are rich in precursor peptides that have antioxidant characteristics (Wen et al., 2020). In watermelon seeds containing 57.1% fat, the unsaturated fat content is 71.9% and 57.40% of these are polyunsaturated fatty acids. Containing essential amino acids (tryptophan, methionine, arginine), minerals such as zinc, iron, phosphorus and vitamins B1, B2, watermelon seeds prevent

FIGURE 1 Sampling map of *Crimson Sweet* watermelon variety.

coronary heart disease and lower blood cholesterol levels (Shahein et al., 2022).

This study aimed to investigate the physical and chemical properties of WBP, which are usually considered waste but contains a significant amount of bioactive compounds. Additionally, the study aimed to assess the potential of these by-products as functional food ingredients.

2 | MATERIALS AND METHODS

2.1 | Material

At the beginning of June 2022, *Crimson Sweet* watermelons were hand-picked after reaching optimum ripeness in agricultural lands situated at 37° 4′ 16.1616′ north latitude and 35° 39′ 36.4248′ east longitude in the Mediterranean Region of Türkiye (Figure 1). Before purchase, the ripeness of the watermelons was checked according to the characteristics specified by Shi et al. (2024). The purchased watermelons had a shiny, hard, and smooth rind color. The stems were hairless and not dry. Afterwards, they were quickly transported to the Food Analysis laboratory at Amasya University Suluova Vocational School, where the outer parts were carefully washed. The peel and rind were properly separated, and the rind was sliced into 8-mm-thick pieces. Seeds were separated from the inner parts of the watermelon and washed with tap water to remove the watermelon parts and sugar. Watermelon rinds, peels, and seeds were dried in an oven (Nuve, FN300, Türkiye) at 50–55°C for 12–14 h. The dried samples were ground with the help of an industrial-type grinder (Arsel, ARSO3, Konya/Türkiye). The finely ground powders were then hermetically sealed and stored at −20°C for subsequent physical and chemical analysis. Figure 2 displayed a graphical summary of the study along with a section of the watermelon's peel, rind, and seed.

2.2 | Physical analysis

2.2.1 | Particle size analysis of WBP

In order to determine the particle size of *WBP* (WSP, WPP, and WRP), a 100 g sample was taken and passed through sieves with diameters of 446, 328, 242, and 109 microns for 5 min. Upon completion, the quantity that remained on each sieve was weighed, and the percentage was calculated (Steckel et al., 2006).

2.2.2 | Water and oil holding capacity of WBP

In order to determine the water holding capacity (WHC), a 0.5-gram sample of each WSP, WPP, and WRP were measured and subsequently mixed with 10 times its weight in water. These mixtures were then vortexed 6 times for 15 s each at 5 min intervals (Velp ZX3, Italy). The samples were then centrifuged at 3,500 rpm for 30 min at 10°C in a centrifuge (Hermle Z206a, Germany). After the separation of the supernatant, the residue was weighed and the WHC was calculated (Toupal, 2022).

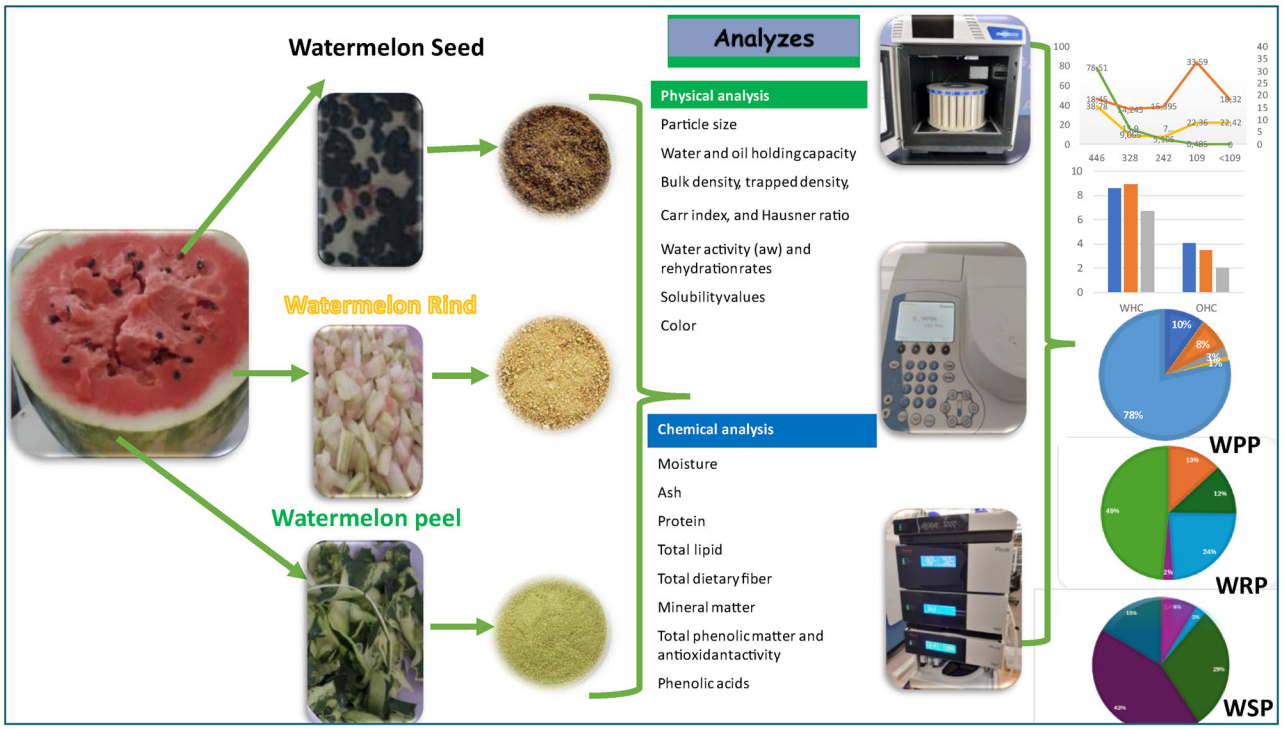

FIGURE 2 Graphical summary of the study along with a section of the watermelon's peel, rind, and, seed.

For oil holding capacity (OHC), 0.5 g of sample was weighed and 5 mL of olive oil was added and vortexed for 30 s (Velp ZX3, Italy). The samples were kept for 1 h at room temperature, centrifuged under the conditions specified in the determination of WHC and the supernatant was removed. After weighing the residue, the OHC was calculated (Toupal, 2022).

2.2.3 | Bulk density, trapped density, Carr index, and Hausner ratio

Bulk density and tapped density of WBP were determined according to Acun (2021). For this purpose, 1 g of sample was weighed and poured into a 10 mL measuring cylinder and the volume was recorded. Tapped density was calculated as the ratio of mass to tapped volume. To determine the tapped density, the mass was compressed by shaking the measuring cylinder 180 times with a hand clapping motion. The tapped volume was determined as a ratio to the mass, and the tapped density was calculated.

After bulk density and tapped density were determined, Carr index and Hausner ratio were calculated for the samples. Carr index and Hausner ratio give information about the fluidity of powders. Fluidity is an important quality factor in the storage and transportation of powders. Powders with excellent fluidity should have a Carr index of less than 10 and a Hausner ratio between 1.00–1.11 (Başyiğit & Çam, 2017).

2.2.4 | Water activity (aw) and rehydration rates of WBP

The water activity of the powders was determined at 25°C with a Novasina LabSwift-aw (Switzerland) measuring device (Akçin & Bostan, 2019). In order to determine the rehydration rate of WSP, WPP, and WRP, 5 g of sample was weighed and 30 times the amount of water was added to it and waited for 50–60 min for soaking. The mixture was then boiled, and the liquid part was filtered. The solid material was carefully placed onto a filter paper, and any excess water was subsequently removed. The solid material is then measured in terms of weight, and the rehydration ratio is calculated as the rehydrated sample weight divided by the dehydrated sample weight. The results are expressed in percentage (Mohan & Shanmugam, 2016).

2.2.5 | Solubility values of WBP

One g of WSP, WPP, and WRP was taken and 10 mL of water was added to it to determine the solubility value. The samples were kept in a shaking water bath (Daihan WSB30, Gangwondo, South Korea) at 80°C for 30 min with continuous shaking and then cooled to room temperature. The cooled samples were centrifuged (Hermle Z206, Germany) at 2200 rpm for 15 min. The supernatant is evaporated, and the residue is weighed to determine the solubility (Mohan & Shanmugam, 2016).

2.2.6 | Color of WBP

L^*, a^* and b^* values of WSP, WPP, and WRP were determined at three different points using a Minolta CR410 (Tokyo, Japan) colorimeter. From the data obtained, the color saturation index (Chroma) was calculated with the formula $\sqrt{(a^{*2} + b^{*2})}$ (Çakır, 2018). Also the Hue value was calculated with the formula given below.

If $a^* > 0$ and $b^* > 0$ $H^\circ = \arctan(b^*/a^*)$;
If $a^* < 0$ and $b^* > 0$, $H^\circ = 180^\circ + \arctan(b^*/a^*)$
If $a^* < 0$ and $b^* < 0$, $H^\circ = 270^\circ + \arctan(b^*/a^*)$
If $a^* > 0$ and $b^* > 0$, $H^\circ = 360^\circ + \arctan(b^*/a^*)$ (Guiné & Barroca, 2012).

2.3 | Chemical analysis

2.3.1 | Moisture, ash and protein content WBP

The moisture content of WBP was determined using AACC Method 44-01,01 (AACC, 2000). Briefly, samples were dried until they reached a constant weight in a hot air oven (Nuve FN 120, Türkiye) at 105°C for 4 hr. The moisture content was calculated as a percentage.

2.3.2 | Ash content

The ash content of the powders was assessed in accordance with AACC Method 08-01.01. (AACC, 2000). Samples were incinerated in a muffle furnace (Nuve MF106, Türkiye) at 600°C for 10 h, resulting in total combustion to a whitish-gray ash. Their ash level was then quantified as a percentage.

2.3.3 | Protein content

About 50 mg of the powder was measured and burned in aluminium tin cups at 900°C using a Dumatherm Nitrogen-Protein analyser (Gerhardt Analytical Systems, Germany) to assess protein levels. Ethylenediaminetetraacetic acid (EDTA, Dumatherm, Germany) was used as a standard reference (Görmez, 2022).

2.3.4 | Total lipid content

Crude fat content was measured using the Soxhlet extraction method, following AAC (2000) Method No. 983.23. Two grams of homogenized samples were placed in a porous thimble and loaded into the extraction chamber of a thermal extraction apparatus. Petroleum ether was used as the solvent and extraction continued for 8 h. Following extraction, the glass cup was dried at 105°C for 1 h, then cooled in a desiccator for about 45 min before being weighed. The fat content was calculated as grams per 100 grams of sample.

2.3.5 | Total dietary fiber content

The defatted samples were first gelatinized using heat-stable alpha-amylase (100°C, pH 6, 30 min), followed by digestion with protease (60°C, pH 7.5, 30 min) and incubation with amyloglucosidase (60°C, pH 4.5, 30 min). After enzymatic treatment, the samples were filtered and thoroughly washed with 78% ethanol, 95% ethanol, and acetone, then dried and weighed to determine the fiber content. The remaining residue, representing the soluble dietary fiber, was also dried and weighed. The total dietary fiber content was then calculated (AACC Method, 32.07.01, 2000).

2.3.6 | Mineral matter

In the Atomic Absorption Spectroscopy (AAS) method, approximately 0.50 grams of samples were weighed with a sensitivity of 0.001 grams and transferred to the Teflon containers of the microwave oven and, 10 mL of concentrated 65% Merck nitric acid was added to each sample. For the blank, 10 mL of 65% nitric acid was added to an empty Teflon container. The lids of the Teflon containers were tightly closed and placed in the CEM brand MARS6 ONE TOUCH (USA) model microwave disintegrator oven. The maximum temperature was increased to 200°C within 15 min and kept at this temperature for 15 min. The dissolution process was carried out by keeping it in the closed system for a total of 30 min. The solutions were read on the Analyst 800 AAS. According to the calibration graph obtained, the results of the samples diluted in a certain amount were obtained in ppm (Mallek-Ayadi et al., 2017).

2.3.7 | Total phenolic matter and antioxidant activity

WBP Extraction

Methanol was used as a solvent for the extraction of phenolic substances from WBP (Baeeri et al., 2018). For extraction, the method suggested by Ahamad et al. (2022) was modified and 0.5 g of sample was taken, 50 mL of methanol was added and extracted at 50°C for 90 min in an ultrasonic water bath (Say Ultrasonic, Istanbul, Türkiye). Then, it was centrifuged at 2000 rpm and the supernatant was used for analysis.

The total phenolic content was measured using the Folin-Ciocalteu reagent method (Singleton & Rossi, 1965). Briefly, a 0.5 mL aliquot of Folin reagent was added to 0.5 mL of the WBP extract. The mixture was stirred and incubated in the dark for 3 min, followed by the addition of 10 mL of Na_2CO_3 solution (75 g/L). The solution was shaken and incubated in the dark for one h. Finally, absorbance was recorded at 750 nm. Total phenolic content was calculated using a standard curve established with gallic acid, and results were expressed as mg of gallic acid equivalents per 100 g of extract (mg GAE/100 g extract). Each value reported is an average of three measurements (Mallek-Ayadi et al., 2017).

Antioxidant activity of WBP was determined according to Aksoylu (2012). For this purpose, 200 μL of the obtained extracts were taken and 3.8 mL of DPPH solution was added. The samples were kept in the dark for 1 h and then read at 515 nm. The results were determined as percentage antioxidant activity.

2.3.8 | Phenolic acids

LC-HRMS analyses were performed using the LC system consisting of a DIONEX UltiMate 3000 RS pump, a DIONEX UltiMate 3000 RS autosampler and a DIONEX UltiMate 3000 RS column oven, and an Exactive Plus Orbitrap (Thermo Fisher Scientific) high-resolution MS combination with a heated electrospray ionization interface. The Orbitrap-MS device was calibrated with positive (Pierce™ LTQ Velos ESI Positive Ion Calibration Solution) and negative calibration (Pierce™ Negative Ion Calibration Solution) solutions using an automatic syringe injector (Thermo Fisher Scientific, USA). In the LC-HRMS analyses, the LC and MS sections were run simultaneously with the TraceFinder 3.2 (Thermo Scientific) program loaded onto the system computer, and the data were collected and recorded with the Xcalibur software version 2.1.0.1140 (Thermo Fisher Scientific) program.

2.3.9 | Chromatography and high resolution MS conditions

A Phenomenex® Gemini® 3 μm NX-C18 110 Å (100 mm × 2 mm) column was used for the performed analyses. The column oven temperature was operated at 30°C. In the elution gradient, 2% (v/v) glacial acetic acid prepared in ultrapure water obtained with the Ultrapure water system (GFL 2004/ Human power 1) was used in the mobile phase A, and 99.9% pure LC-MS grade methanol (Sigma) was used in the mobile phase B. Separation was performed under gradient elution conditions with a sample injection volume of 20.0 μL and a flow rate of 0.3 mL/min. The analysis time was set to 20 min in total. Orbitrap HRMS equipped with a heated electrospray ionization interface was operated in both positive (Full MS/AIF) and negative (Full MS/AIF) modes. The ionization interface was set to sheath gas flow rate 35; auxiliary gas flow rate 7; spray voltage 3.5 kV; capillary temperature 350°C; auxiliary gas temperature 350°C; S-lens RF level 50. MS scan range 60–800 m/z; resolution 17,500; ACG target 3.106; maximum IT 2 ms; CE (collision energy, step CE)/ 25 V conditions. For phytochemical compounds belonging to LC–Orbitrap HRMS analysis method, Apigenin standard concentration 10ppb-20ppb-40ppb-60ppb-80ppb-100ppb-200ppb-300 ppb-400ppb-500 ppb was prepared and each was injected in three replicates. 1 g of the sample was weighed and mixed in a 50% methanol-pure water mixture in an ultrasonic bath for 10 min, then shaken in an orbital shaker at 200 rpm for 2 h. Then, it was centrifuged at 4500 rpm for 10 min and taken from the upper liquid phase and filtered through a 25 mm diameter PTFE syringe filter with a pore size of 0.22 μm with the help of a 10 mL syringe and injected into the device by taking a 1.5 mL vial (Mallek-Ayadi et al., 2017).

2.4 | Statistical analysis

The WBP were analyzed using analysis of variance, and the mean values were compared using the Duncan Multiple Comparison test in the SPSS Version 26.0 software program (Singh et al., 2023).

3 | RESULTS AND DISCUSSION

3.1 | Physical properties of WBP

3.1.1 | Particle size of WBP

Understanding the particle size distribution of powders is essential for quality control, packaging, transportation, processing, product development, and research. The physical characteristics of a food powder, including its bulk density, compressibility, and flowability, are greatly influenced by particle size and size distribution (Barbosa-Cánovas et al., 2012). Controlling the distribution of particle sizes is one way to optimise food processing (Servais et al., 2002). Figure 3 shows the amounts remaining on each sieve after 5 min of sieving 100 grams of WPP, WRP, and WSP through 446, 328, 242, and 109-micron sieves. Significant differences were observed between particle sizes ($p < 0.05$) of WSP, WPP, and WRP. The majority of WSP (78.51%) exhibited a particle size larger than 446 microns, with no particle size below 109 microns detected. WSP has the largest

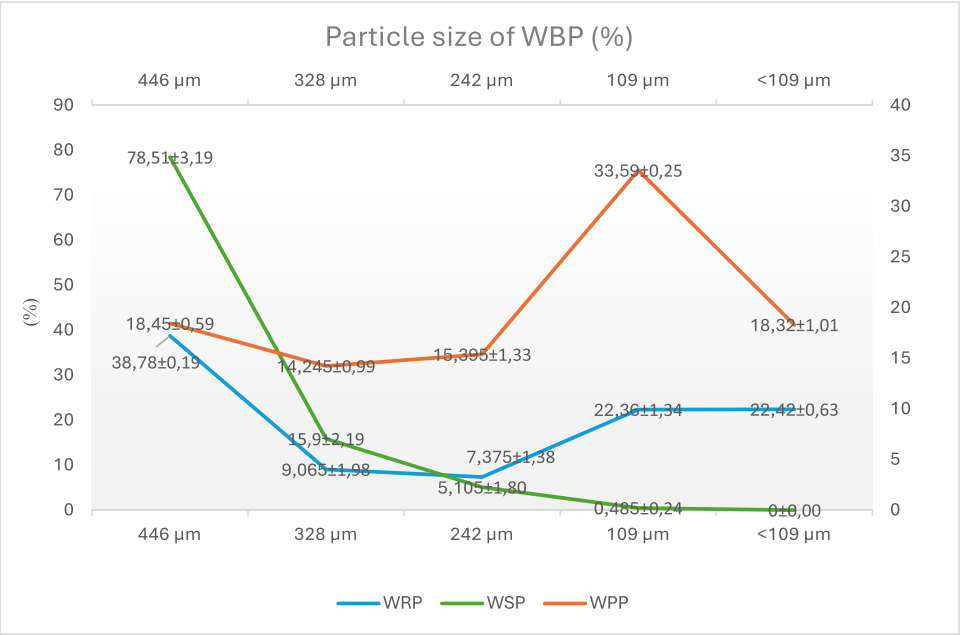

FIGURE 3 Particle sizes of WBP. WBP: Watermelon by-product powders. WPP: Watermelon peel powder. WRP: Watermelon rind powder. WSP: Watermelon seed powder.

particle size among the three samples. This is because, despite using the same grinder and the same grinding time, the hard structure of watermelon seeds prevents them from grinding to fine sizes. After WSP, the sample with the second largest size was WRP. However, both WRP and WPP exhibited a heterogeneous size distribution. Note that, 38.78% of WRP has a particle size above 446 microns, while 44.78% has a particle size below 109 microns and 51.91% of WPP is below 109 microns. This heterogeneity impacts the quality of the products it utilizes, and it also plays a crucial role in powder storage and transportation. As the particle size decreases, the increasing surface ratio leads to an increase in the attraction force between particles and the possibility of bridging, thus decreasing the fluidity (Jan et al., 2015). Long et al. (2024) highlighted that the particle size of the watermelon rind powder significantly influences nutritional composition, textural and cooking qualities of the pasta. They found that soluble dietary fibre content of pasta increased by 35% and total phenolic content by 15%, and the glycemic index of the pasta increased from 50 to 69 while insoluble dietary fibre decreased by 21%.

3.1.2 | WHC and OHC of WPB

WHC and OHC values of WSP, WPP, and WRP are given in Table 1. The difference between these two values of the powders was statistically significant ($p < 0.05$). WSP has the lowest WHC (6.69%) and OHC (5.06%). This can be attributed to the larger particle size of WSP compared to WRP and WPP. 51.91% and 44.78% of WPP and WRP, respectively, have a particle size below 242 microns, and the WHC and OHC of these two by-products were found to be higher than that of WSP, which has almost no particle size below 242 microns. There is an inverse relationship between the particle size of the powders and WHC. Additionally, powders with finer particle sizes may expose hydrophilic groups in cellulose and hemicelluloses, facilitating easy integration with water and consequently increasing the WHC value (Zhao et al., 2009).

TABLE 1 Water holding capacity (WHC) and oil holding capacity (OHC) of watermelon by-products (WBP).

Sample	WHC(%)	OHC(%)
WPP	8.59 ± 0.01^{b}	4.09 ± 0.41^{a}
WRP	8.89 ± 0.02^{a}	3.47 ± 0.11^{b}
WSP	6.69 ± 0.11^{c}	2.06 ± 0.15^{c}

Abbreviations: OHC, Oil holding capacity: WHC, Water holding capacity; WBP, Watermelon by-product powders; WPP, Watermelon peel powder; WRP, Watermelon rind powder; WSP, Watermelon seed powder.

[abc]There is no statistical difference between the data shown with the same letter in the same column.

The starch content of watermelon rind dried with hot air varies between 3.28%–4.24% and the amount of resistant starch increases as the applied heat increases (Ho et al., 2017). The temperature applied during the drying of the WBP used in the study caused the starch in the WSP to retain more water. Since WSP contains more oil, it is thought that the damage to starch in WSP is not as high

TABLE 2 Density and fluidity values of WBP.

Sample	Bulk density (g/mL)	Tapped density (g/mL)	Carr index	Hausner ratio
WPP	0.44 ± 0.02^{b}	0.47 ± 0.03^{a}	11.36 ± 1.97^{b}	1.17 ± 0.04^{a}
WRP	0.48 ± 0.00^{a}	0.40 ± 0.00^{b}	14.67 ± 2.31^{ab}	1.17 ± 0.03^{a}
WSP	0.43 ± 0.01^{b}	0.50 ± 0.00^{a}	18.02 ± 0.17^{a}	1.22 ± 0.03^{a}

Abbreviations: WBP, Watermelon by-product powders; WPP, Watermelon peel powder; WRP, Watermelon rind powder; WSP, watermelon seed powder.
[abc]There is no statistical difference between the data shown with the same letter in the same column.

as in WRP due to the heat treatment applied. Ho et al. (2017) conducted a study to investigate the characteristics of watermelon rind that had been subjected to varying drying temperatures, and their findings were consistent with those of the present study.

Watermelon peel is high in water-soluble fiber and pectin (Lee & Choo, 2020; Naknaen et al., 2016). The high WHC of the peel may be due to this. It was reported that the water and oil retention rate of WRP varied between 3.29%–11.04% and 2.32%–3.73%, respectively (Ho et al., 2017; Mohan & Shanmugam, 2016; Naknaen et al., 2016). The results obtained were within the value range specified in the literature. WHC and OHC of watermelon seeds were reported in the literature as 7.13% and 1.65%, respectively (Egbuonu, 2015). Also, the WHC and OHC of WSP is similar to the literature.

3.1.3 | Density properties of WBP

Density properties of WBP are given in Table 2. Bulk density of WBP ranged between 0.43–0.48 g/mL, while tapped densities ranged between 0.40–0.51 g/mL. Bulk density is directly related to particle size (Jan et al., 2015). In this regard, it was found that the bulk density of WRP, which had a larger particle size compared to WPP, have a higher value. The low bulk density of WSP, whose particle size is larger than other powders, is thought to be due to the high fat content in its composition. Mohan & Shanmugam (2016) reported that the bulk density of conventional and freeze-dried watermelon rind powders ranged between 0.09-0.40 g/mL, while the tapped density ranged between 0.11–0.56 g/mL. Bulk density and tapped density of WBP dried conventionally in an oven showed similar results to the literature.

The Carr index is a significant parameter in the context of powder product storage and transportation, as it provides information about the strength and stability of powders. On the other hand, the Hausner ratio is an indicator of the inter-particle friction within powders. In the case of powders exhibiting high fluidity, it is preferable for these values to be minimized (Başyiğit & Çam, 2017; Jan et al., 2015). The Carr index of WBP varies between 11.36–18.02, while the Hausner ratio varies between 1.17–1.22. Although there was no statistical difference between the powders in terms of Hausner ratio, WSP had the highest value in terms of Carr index values ($p < 0.05$). Powders with excellent fluidity should have a Carr index of 11–15 and a Hausner ratio of 1.12–1.18, while powders with medium fluidity should have a Carr index and Hausner ratio of 16–20 and 1.19–1.25, respectively (Jan et al., 2015). According to the data obtained, WPP and WRP have excellent fluidity while WSP has medium fluidity. Mohan & Shanmugam (2016) who stated that powder fluidity changes linearly with product moisture, reported the Carr index of freeze-dried watermelon rinds as 18.18 and Hausner ratio as 1.22. The Carr index of the watermelon rind powder, which was dried by applying hot air and whose moisture content was higher than the freeze-dried one, was reported as 28.57 and Hausner ratio as 1.40. The fluidity property of WSP, which has lower water activity and larger particle size, shows a difference from the literature in this regard. WSP, which has a larger particle size than other powders, is expected to show more fluidity due to the low inter-particle cohesion strength. It is thought that this result, which is different than expected, is due to the chemical composition of WSP and that the interaction of fat, sugar, and protein in its structure affects the fluidity.

3.1.4 | Water activity, rehydration, and solubility characteristics of WBP

Table 3 provides the water activity, rehydration ratio, and solubility values of WBP. The water activity value of WBP ranged between 0.468 and 0.507, the rehydration ratio between 4.05%–7.85%, and the solubility value between 7.12%–14.42%.

Water activity refers to the percentage of free water that causes microbial spoilage and spoilage caused by chemical and enzymatic reactions, and products with a water activity above 0.6 require a preservation method such as low temperature storage to prevent the growth of pathogens or other spoilage-causing microorganisms (Fundo et al.,

TABLE 3 Water activity, rehydration ratio and solubility of WBP.

Sample	aw	Rehidration rate (%)	Solubility (%)
WPP	0.507 ± 0.00[a]	7.26 ± 0.03[b]	11.56 ± 0.09[b]
WRP	0.468 ± 0.00[b]	7.85 ± 0.12[a]	14.42 ± 0.31[a]
WSP	0.483 ± 0.00[c]	4.05 ± 0.17[c]	7.12 ± 0.54[c]

[abc]There is no statistical difference between the data shown with the same letter in the same column.

Abbreviations: aw, Water activity; WBP, Watermelon by-product powders; WPP, Watermelon peel powder; WRP, Watermelon rind powder; WSP, watermelon seed powder.

2018). The water activity of all WBP was determined to be below 0.6.

The rehydration ratio of WRP was found to be higher than other powders. The high rehydration ratio of powders is seen as an advantage in ready-to-eat food production and it has been reported in the literature that the rehydration ratio of watermelon rind is between 4.4%–11.40% (Mohan & Shanmugam, 2016). The rheydration rate and solubility of WSP were found to be considerably lower than the other by-products, namely WRP and WSP. This can be attributed to the larger particle size of WSP. Rehydration rate and solubility are inversely proportional to particle size. Similarly, Zhao et al. (2009) reported that the water solubility index increased significantly with decreasing particle size of ginger particles. The solubility of watermelon rind has been reported in the literature to range from 5.12% to 11.29%. The use of high temperatures during the drying of watermelon rinds causes the breakdown of large structured components such as starch into simple sugars (Mohan & Shanmugam, 2016). The starch content of watermelon seeds ranges between 143.7–163.9 mg/g (Falade et al., 2020), and the starch content of watermelon rind ranges between 2.24%–2.69% (Ho et al., 2017). The soluble sugar in the structure of WRP and the starch broken down by the effect of heat applied during drying increased the solubility value.

3.1.5 | Color values of WBP

The averages of the color characteristics of WBP are presented in Table 4. L^* shows brightness, a^* shows redness-greenness (±), b^* shows yellowness-blueness (±) and Hue shows color angle. If the Hue value is between 0°–90° it is red, between 90°–180° it is yellow, between 180°–270° it is green and between 270°–360° it is blue (Balbaba & Bağcı, 2022).

L^* value of watermelon by-product powders varied between 37.29–67.66. The darker color of WSP caused the L^* value to decrease, while the lighter colored WRP had the highest L^* value. In terms of redness value (a^*), WSP has the highest value with 3.41, while WPP has a negative a^* value (-6.16), which is an indicator of green color (Figure 4).

WRP has the highest b^* (21.94) and Chroma (21.91) values while WSP has the lowest Hue (71.56) and Chroma (10.84) values. The proximity of the Hue value of WRP to 90 suggests that it has a yellow hue, while the raised b^* value indicates a favorable connection with the analysis results. Mohan & Shanmugam (2016) determined L^*, a^*, and b^* values of WRP as 62.51/77.22, -0.38/-1.67, 19.8/21.2, respectively. Croma values of WBP ranged between 10.84–21.91, with WSP having the lowest Croma value.

3.2 | Chemical properties of WBP

3.2.1 | Proximate composition

Table 5 reveals statistically significant differences ($p > 0.05$) in the moisture, ash, protein, total lipid, and dietary fibre contents of WBP. When the by-products were compared in terms of moisture content, it was observed that WRP had the highest with 13.09% while WSP had the lowest with 8.70%. WRP had also higher moisture content than WPP. These results are agreement with Al-Sayed & Ahmed (2013) who, reported that WRP had higher moisture as compared to sharlyn melon peel powder. The higher moisture content of the WRP after drying can be attributed to the high moisture content of the watermelon and watermelon rind. Water makes up over 91% of watermelon (Al-Sayed & Ahmed, 2013). Al-Sayed & Ahmed (2013) and Hoque & Iqbal (2015) reported the moisture content of WRP as 10.61% and 10.72%, respectively. Variations in the watermelon cultivar, environment, soil, climate, and/or drying methodology, compared to the available literature, may account for the high moisture content of WRP in this study.

There were notable variations ($p > 0.05$) in the amount of ash present in the WBP. WRP was determined to have the highest ash quantity, followed by WPP, and WSP to have the lowest. Both WRP and WPP contain high levels of ash, or minerals, indicating their high nutritional content and potential for use as novel food additives. In comparison to our findings, Al-Sayed & Ahmed (2013) and Feizy et al. (2020) reported higher ash contents for WRP (13.09%), Sharlyn melon peels (11.09%), and WPP (13.2%).

The protein content of WRP and WSP is considerably higher than WPP. This notable variation in protein levels suggests the use of WRP and WSP as food additives, especially for diets seeking a higher protein content. Furthermore, this may be particularly beneficial for individuals who aim to increase their protein intake. The protein content of WSP in the current study is much higher

TABLE 4 Color values of WBP.

Sample	*L**	*a**	*b**	Hue	Chroma
WPP	58.37 ± 0.67[b]*	−6.16 ± 0.14[c]	17.79 ± 0.30[b]	109.10 ± 0.15[a]	18.83 ± 0.33[b]
WRP	67.66 ± 0.27[a]	1.08 ± 0.09[b]	21.94 ± 0.09[a]	87.19 ± 0.24[b]	21.91 ± 0.09[a]
WSP	37.29 ± 0.64[c]	3.41 ± 0.03[a]	10.34 ± 0.11[c]	71.56 ± 0.32[c]	10.84 ± 0.10[c]

Abbreviations: WBP, Watermelon by-product powders; WPP, Watermelon peel powder; WRP, Watermelon rind powder; WSP, watermelon seed powder.
[abc]There is no statistical difference between the data shown with the same letter in the same column.

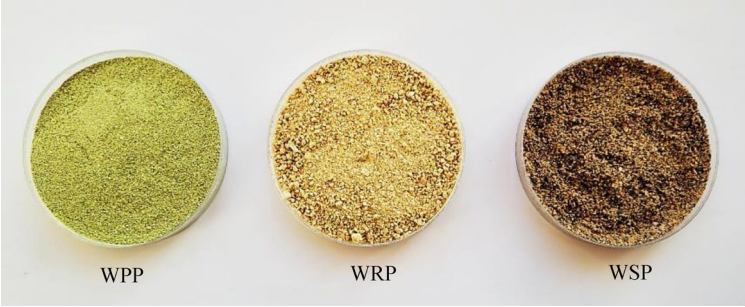

FIGURE 4 Images of WPP (Watermelon peel powder). WRP (Watermelon rind powder). WSP (Watermelon seed powder).

TABLE 5 Moisture, ash, protein, total lipid, and total dietary fiber content of WBP.

Sample	Moisture (%)	Ash(%)	Protein(%)	Total Lipid (%)	Total Dietary Fiber (%)*
WPP	9.96 ± 0.15[b]*	7.99 ± 0.00[b]	2.56 ± 0.02[c]	0.94 ± 0.01[b]	78.55 ± 0.29[a]
WRP	13.09 ± 0.11[a]	12.07 ± 0.09[a]	23.74 ± 0.01[b]	2.44 ± 0.02[b]	48.66 ± 1.88[b]
WSP	8.70 ± 0.06[c]	2.56 ± 0.07[c]	29.46 ± 0.01[a]	43.00 ± 2.00[a]	16.28 ± 0.21[c]

Abbreviations: WBP, Watermelon by-product powders; WPP, Watermelon peel powder; WRP, Watermelon rind powder; WSP, watermelon seed powder.
* Dry matter basis.
[abc]There is no statistical difference between the data shown with the same letter in the same column.

compared to 16.33%–17.75% reported for seed powders obtained from three different watermelon varieties (Tabiri et al., 2016). Similarly, Wani et al. (2008) reported lower protein contents (16.34 ± 0.59) for watermelon seeds. Variations in plant material, equipment type used for drying, and other agricultural factors during growth conditions can account for the discrepancy in the reported findings.

Significant differences were also observed in the total lipid content of WBP (Table 6). WRP had 2.44% total lipids, while WPP had 0.94%. However, WSP had 43.00% total lipids, significantly higher than the others. The total lipid content of WSP is within the range of literature, including those by Gabriel et al. (2018), Keke et al. (2023), Oyeleke et al. (2012), who observed crude lipid content values of 21.54%, 43% and 47.9% in WSP, respectively. These findings highlight the variability in lipid content across different studies and the potential influence of environmental factors, processing methods, or species variation. As can be seen from our findings, watermelon seeds, which are a waste product, are a potential resource that can be used in oil production. The physicochemical qualities of watermelon seed oil align with the recommended requirements, indicating its suitability as a cooking and frying oil (Biswas et al., 2017). However, watermelon seed oil can also protect liver cells from harmful substances thanks to its high concentration of linoleic acid and other saturated fatty acids (Eke et al., 2021). Watermelon seed oil has nutritional significance and offers numerous health benefits, including immune system protection, support in treating obesity, depression, and bone health, as well as the prevention of cardiovascular disease through the reduction of intestinal cholesterol absorption (Benmeziane & Derradji, 2023; Saibu et al., 2024).

Hussain et al. (2024) analyzed the proximate composition of watermelon peels and found the moisture, ash, lipid, and protein contents to be 7.15%, 7.04%, 0.99%, and 4.78%, respectively. This is in line with the current study but with slightly higher protein levels.

Among WBP, WPP has the highest dietary fiber content, at 78.55% (Table 5). Although the dietary fiber content of WRP is high, it is lower than that of WPP. However, among the three samples, WSP had the lowest dietary fiber content. The high fat and protein content of WSP is an important factor in its low dietary fiber content. The

TABLE 6 Mineral matter content (ppm) of WBP.

Sample	Mineral Matters (ppm)			
	Fe	Mg	K	Na
WPP	18.95 ± 0.02[c]	2690.19 ± 0.06[b]	19,168.36 ± 0.07[b]	19.28 ± 0.01[c]
WRP	22.48 ± 0.40[b]	2751.94 ± 0.61[a]	33,369.86 ± 0.79[a]	40.73 ± 0.41[b]
WSP	25.9 ± 0.01[a]	2115.25 ± 0.06[c]	11,092.5 ± 0.09[c]	46.8 ± 0.01[a]

Abbreviations: WBP, Watermelon by-product powders; WPP, Watermelon peel powder; WRP, Watermelon rind powder; WSP, watermelon seed powder.
[abc]There is no statistical difference between the data shown with the same letter in the same column.

present study's WRP result exceeded that of Pires et al. (2023), who reported a total dietary fiber content of 27.15% in watermelon rind flour. Similarly, lower results for fiber content in watermelon (*Citrullus lanatus, var. Augusta*) peel powder, watermelon rind, and sharlyn melon peel powder—7.59%, 17.28% and 29.59%, respectively—were mentioned by Al-Sayed & Ahmed (2013) and Hussain et al. (2024). On the other hand, the results from Naknaen et al. (2016) for WRP with 68.43 g/100 g total dietary fibre were higher than our findings.

WPP and WRP, due to their high fibre content, can enhance the dietary fibre levels in various foods. Furthermore, the incorporation of WRP into bread formulations improves the bread's quality (Romdhane et al., 2024). Norazman et al. (2024) reported that the inclusion of WRP in yogurt significantly enhanced the growth of probiotic bacteria, increasing from 7.20 ± 0.22 log CFU/mL in the control sample (0% WRP) to 8.42 ± 0.23 log CFU/mL in the sample containing 4% WRP after 30 h of incubation. This indicates that WRP can effectively support the growth of beneficial bacteria in fermented milk products. Chemical composition of watermelon byproducts supports their inclusion in various dietary patterns, making them valuable for meeting daily nutritional requirements (Meghwar et al., 2024).

3.2.2 | Mineral matter content of *WBP*

Mineral content (Fe, Mg, K and Na) of the watermelon by product powders are presented Table 6.

There was a highly significant difference ($p < 0.05$) between WPP, WRP, and WSP in terms of all measured minerals. The Mg and K content of WBP was observed to be significantly higher than that of Fe and Na. In this context, the K and Mg content of WRP was notably higher than that of the others. Gabriel et al. (2018) also reported the high concentration of calcium and magnesium in watermelon seeds, leading them to recommend it as a bone- and teeth-strengthening element and a potential ingredient for stimulation and revitalization in cosmetics. Feizy et al. (2020) found 53.59 mg/100 g sodium, 2074 mg/100 g potassium, 12.08 mg/100 g iron, and 164.48 mg/100 g magnesium in watermelon peel in a similar study. In general, there are differences between the studies in the literature and our findings regarding the minerals and other constituents of WBP. These differences stem from variations in the watermelon varieties under analysis, as well as variations in the soil and climate, as previously mentioned.

3.2.3 | Total phenolic matter, antioxidant activity, and phenolic acids of *WBP*

The total phenolic content and antioxidant capacity (IC50) of WBP were quantified and are presented in Table 7.

The total phenolic content was determined to be 4196.5, 2855, and 3330 mg GAE/100 g for the WPP, WRP, and WSP, respectively. The peel of the watermelon demonstrated the greatest concentration of total phenolics, in contrast to the rind, which exhibited the least. A comparative study examining the antioxidant and antimicrobial properties of various watermelon (*Citrullus lanatus*) parts revealed that the total phenolic content of the peel, rind, and seeds was quantified as 0.087 mg GAE/g, 0.026 mg GAE/g, and 0.042 mg GAE/g, respectively (Neglo et al., 2021). A consistent trend was observed in both studies, where the watermelon peel exhibited the highest total phenolic content, followed by the seeds, and the inner rind displayed the lowest.

Zia et al. (2024) reported lower phenolics (0.95–1.55 mg gallic acid g−1) in freeze-dried watermelon rind of *Crimson Sweet* variety, when compared with the results of the current study, which might be due to differences in environmental factors, location, soil conditions, maturity level, and harvesting time.

Similarly, the antioxidant activity, as measured by IC50 values, was highest in the WPP (44.42 mg/mL) and lowest in the WRP (121.29 mg/mL). A comparative analysis of WBP revealed that the peel exhibited the most significant DPPH radical scavenging activity with a percentage inhibition of 55.75%, whereas the rind demonstrated the least activity at 34.48% (Neglo et al., 2021). A study investigating the utilization of watermelon and sharlyn peels as natural

TABLE 7 Total phenolic matter and antioxidant activity of WBP.

Örnek	Total phenolic matter (mg GAE/100 g sample)	Antioxidant activity (IC_{50} mg/mL)
WPP	4196.5 ± 47.37[a]	44.42 ± 0.02[b]
WRP	2855.0 ± 35.35[c]	121.29 ± 0.01[a]
WSP	3330.0 ± 141.42[b]	67.36 ± 0.02[b]

Abbreviations: WBP, Watermelon by-product powders; WPP, Watermelon peel powder; WRP, Watermelon rind powder; WSP, watermelon seed powder.
[abc]There is no statistical difference between the data shown with the same letter in the same column.

sources of dietary fiber and antioxidants in cakes revealed that the inner rind of watermelon exhibited a DPPH inhibition percentage of 39.7% (Al-Sayed & Ahmed, 2013). In the study investigating watermelon rind extract, the IC50 value was determined to be 0.64 mg/mL (Romdhane et al., 2017). The significant radical scavenging activity of this extract can be attributed to the presence of hydroxyl and carboxyl groups, particularly in galacturonic acid residues of polysaccharides. These functional groups act as hydrogen donors, effectively scavenging DPPH free radicals and mitigating oxidative stress (Cheng et al., 2013; Nara et al., 2009). The study by Zia et al. (2024) demonstrated that watermelon rind extracts, obtained through optimized ultrasound-assisted extraction, showed high antioxidant activities, measured by DPPH (22–40 mg Trolox/g) and FRAP (26–42 mg ferrous sulfate/g) assays. These findings suggest that the phenolic compounds present in WBP possess significant antioxidant properties, and a direct correlation was observed between the total phenolic content and the antioxidant activity. The literature suggests a strong correlation between phenolic compounds and antioxidant activity in plant-based products. The observed higher antioxidant activity in the peel, characterized by its abundant phenolic content, compared to the pulp, supports the hypothesis that these phenolic compounds are primarily responsible for the antioxidant effects (Generalić Mekinić et al., 2019).

The DPPH radical scavenging activities of 13 different red and white Spanish grapes have been reported between 72.95 ± 2.21–230.67 ± 11.71 μmol TE/g DW for red grapes and 29.50 ± 1.57–206.80 ± 10.45 μmol TE/g DW for white grapes (Elejalde et al., 2022). It is difficult to directly compare the results of the current study with the previous studies due to the fact that different formats (quercetin equivalent or trolox equivalent, etc.) were used for the expression of DPPH values. In another study evaluating the pomace, peel, and seeds of 30 different grape varieties, the highest antioxidant activity was found in the seeds (Tang et al., 2018). Additionally, a study investigating the antioxidant activity of 8 different grape varieties reported IC_{50} values ranging from 30.63 to 149.78 mg/mL (Meziane et al., 2023). When the antioxidant activity of grape varieties was compared to watermelon by-products, it was found that all watermelon by-products exhibited antioxidant activity similar to that of grapes. Specifically, the watermelon seed (67.36 mg/mL) was determined to have an antioxidant activity close to the Cardinal grape variety (69.56 mg/mL). A review of the literature indicates that the IC_{50} values for BHA and BHT, which exhibit significant antioxidant activity, are reported to range between 6.42–17.3 and 35.5–48.50, respectively (Han et al., 2018; Kalin et al., 2015; Koksal et al., 2011). Based on these values, it can be concluded that the antioxidant activity of watermelon rind and seed is comparatively lower than that of BHA and BHT, whereas the antioxidant activity of watermelon peel is relatively close to that of BHT. The total phenolic content of Concord and Niagara grapes has been reported as 21.9–50.7 mg per 100 g fresh weight (fw) and 2.9–9.6 mg per 100 g fw, respectively (Mohamedshah et al., 2020). When compared to these values, the total phenolic content of watermelon by-products was found to be significantly higher.

A total of 47 phenolic acids were characterized in the present study, and, they are listed in Table 8.

The phenolic compounds in the WPP were identified as follows, from lowest to highest quantity: chlorogenic acid (1.96 μg/kg), taxifolin (51.39 μg/kg), caffeic acid (101.04 μg/kg), phenyl ester naringenin (165.28 μg/kg), luteolin (192.3 μg/kg), protocatechuic acid (180.63 μg/kg), galangin (200.92 μg/kg), 3,4-dihydroxybenzaldehyde (879.03 μg/kg), vanilic acid (2826.1 μg/kg), and leucoside (6249.77 μg/kg). Quantitative analysis of the WPP revealed the presence of several phenolic compounds. The most abundant compound identified was genistein (10147.1 μg/kg), followed by phloridzin (9988.47 μg/kg), eriodictyol (6822.37 μg/kg), trans-cinnamic acid (3142.88 μg/kg), astragalin (893.45 μg/kg), coumaric acid (652.11 μg/kg), kaempferitrin (555.27 μg/kg), rhoifolin (55.18 μg/kg), and sinopic acid (18.38 μg/kg).

Quantitative analysis of WSP revealed the presence of a diverse range of phenolic acids. The major compounds identified included narirutin, 3-(4-hydroxyphenyl) propionic acid, liquiritigenin, rosmarinic acid, and L-ascorbic acid. Other significant phenolic compounds found were

TABLE 8 Phenolic acid content (μg/kg) of WBP.

No	Phenolic acids	WPP	WRP	WSP
1	Benzoic acid	147.97 ± 0.01[c]	396.34 ± 0.06[b]	1443.51 ± 0.02[a]
2	4-Hydroxybenzoic acid	0.00 ± 0.00[b]	3942.72 ± 0.07[a]	0.00 ± 0.00[b]
3	Syringic acid	0.00 ± 0.00[b]	795.47 ± 0.06[a]	0.00 ± 0.00[b]
4	Protocatechuic acid (3,4-Dihydroxybenzoic acid)	180.63 ± 0.01[a]	0.00 ± 0.00[b]	0.00 ± 0.00[b]
5	3,4-dihydroxy benzaldehyde (Protocatechuic aldehyde)	879.03 ± 0.03[a]	0.00 ± 0.00[c]	678.02 ± 0.34[b]
6	Vanillic acid	2826.1 ± 0.07[a]	407.05 ± 0.64[b]	0.00 ± 0.00[c]
7	Vanillin	1500.67 ± 0.09[b]	484.45 ± 0.09[c]	4539.07 ± 0.06[a]
8	Gentisic acid	6.72 ± 0.01[b]	0.00 ± 0.00[c]	101.54 ± 0.02[a]
9	3,4-Dihydroxy phenyl acetic acid (DOPAC, Homoprotocatechuic acid)	0.00 ± 0.00[c]	1750.73 ± 0.43[b]	3584.15 ± 0.04[a]
10	trans Cinnamic acid	765.53 ± 0.02[c]	3142.88 ± 0.67[a]	2397.42 ± 0.05[b]
11	Coumaric acid (trans-3-Hydroxycinnamic acid)	90.25 ± 0.01[c]	652.11 ± 0.04[a]	397.97 ± 0.02[b]
12	Caffeic acid	135.15 ± 0.06[b]	0.00 ± 0.00[c]	1614.94 ± 0.06[a]
13	Caffeic acid phenhyl ester (CAPE)	101.04 ± 0.01[a]	16.97 ± 0.03[b]	0.00 ± 0.00[c]
14	Ferulic acid	252.63 ± 0.01[b]	69.74 ± 0.04[c]	5039.18 ± 0.06[a]
15	Sinapic acid	0 ± 0.00[b]	18.38 ± 0.01[a]	0.00 ± 0.00[b]
16	Chlorogenic acid	1.96 ± 0.01[a]	0.00 ± 0.00[b]	0.00 ± 0.00[b]
17	3-(4-Hydroxyphenyl) propionic acid	0.00 ± 0.00[b]	0.00 ± 0.00[b]	7648.14 ± 0.06[a]
18	L-ascorbic acid	3261.71 ± 0.06[b]	3797.02 ± 0.04[b]	5352.55 ± 0.06[a]
19	α-Cyano-4-hydroxycinnamic acid	0.00 ± 0.00[c]	42.31 ± 0.04[b]	114.19 ± 0.01[a]
20	Chrysin (5,7-Dihydroxy-2-phenyl-4H-chromen-4-one)	0.00 ± 0.00[b]	0.00 ± 0.00[b]	142.5 ± 0.03[a]
21	Apigenin (5,7-Dihydroxy-2-(4-hydroxyphenyl)-4H-chromen-4-one)	0.00 ± 0.00[b]	0.00 ± 0.00[b]	3103.2 ± 0.06[a]
22	Rhoifolin (Apigenin 7-O- neohesperidoside)	0.00 ± 0.00[b]	55.18 ± 0.02[a]	0.00 ± 0.00[b]
23	Vicenin 2	97.62 ± 0.03[c]	120.41 ± 0.07[b]	193.2 ± 0.03[a]
24	Apigenin 7-glucoside	0.00 ± 0.00[c]	0.00 ± 0.00[c]	11.54 ± 0.01[a]
25	Genkwanin (4′,5-Dihydroxy-7-metthoxyflavone, Apigenin 7-O-methyl ether)	0.00 ± 0.00[b]	0.00 ± 0.00[b]	247.31 ± 0.05[a]
26	Schaftoside	0.00 ± 0.00[b]	0.00 ± 0.00[b]	67.06 ± 0.02[a]
27	Rutin hydrate M-OH2	40.99 ± 0.03[b]	40.64 ± 0.46[b]	150.88 ± 0.04[a]
28	Luteolin	192.3 ± 0.06[a]	32.55 ± 0.04[b]	0.00 ± 0.00[c]
29	Orientin	428.62 ± 0.04[b]	0.00 ± 0.00[c]	856.95 ± 0.06[a]
30	Isoorientin	428.62 ± 0.08[b]	0.00 ± 0.00[c]	796.28 ± 0.02[a]
31	Luteoloside (Luteolin 7-glucoside)	0.00 ± 0.00[b]	0.00 ± 0.00[b]	222.42 ± 0.06[a]
32	Galangin (3,5,7-Trihydroxy-2-phenyl-4H-chromen-4-one)	200.92 ± 0.06[a]	94.84 ± 0.03[b]	0.00 ± 0.00[c]
33	Quercetin	22.58 ± 0.02[b]	15.34 ± 005[c]	75.72 ± 0.02[a]
34	Afzelin (Kaempferol 3-rhamnoside)	0.00 ± 0.00[b]	0.00 ± 0.00[b]	98.09 ± 0.07[a]
35	Kaempferitrin	0.00 ± 0.00[b]	555.27 ± 0.73[a]	0.00 ± 0.00[b]
36	Astragalin (Kaempferol 3-glucoside)	0.00 ± 0.00[b]	893.43 ± 0.42[a]	0.00 ± 0.00[b]
37	Leucoside (Kaempferol 3-sambubioside)	6249.77 ± 0.05[a]	6248.33 ± 0.04[b]	6233.52 ± 0.03[c]
38	Naringenin	165.28 ± 0.01[a]	42.27 ± 0.31[b]	27.01 ± 0.01[c]
39	Narirutin (Narirutinsa, Naringenin rutinoside)	0.00 ± 0.00[b]	0.00 ± 0.00[b]	20,738.74 ± 0.06[a]
40	Taxifolin M+3H	51.39 ± 0.05[a]	0.00 ± 0.00[b]	0.00 ± 0.00[b]
41	Eriodictyol (3,4,5,7-Tetrahydroxyflavanone)	8.9 ± 0.01[c]	6822.37 ± 0.45[a]	67.99 ± 0.06[b]
42	Liquiritigenin	0.00 ± 0.00[b]	0.00 ± 0.00[b]	7653.22 ± 0.08[a]

(Continues)

TABLE 8 (Continued)

No	Phenolic acids	WPP	WRP	WSP
43	Genistein (5,7-Dihydroxy-3-(4-hydroxyphenyl)-4H-chromen-4-one)	10145.19 ± 006[b]	10147.1 ± 0.04[a]	10143.26 ± 0.09[c]
44	Esculin hydrate	62.76 ± 0.01[a]	43.25 ± 0.47[b]	43.11 ± 0.03[b]
45	Phloridzin	9927.94 ± 0.09[b]	9988.47 ± 0.64[a]	0.00 ± 0.00[c]
46	Rosmarinic acid	0.00 ± 0.00[b]	0.00 ± 0.00[b]	6464.71 ± 0.07[a]
47	Arbutin	0.00 ± 0.00[b]	0.00 ± 0.00[b]	309.37 ± 0.06[a]

Abbreviations: WBP, Watermelon by-product powders; WPP, Watermelon peel powder; WRP, Watermelon rind powder; WSP, watermelon seed powder.
[abc]There is no statistical difference between the data shown with the same letter in the same column.

ferulic acid, vanillin, 3,4-dihydroxyphenylacetic acid, apigenin, caffeic acid, benzoic acid, orientin, isoorientin, arbutin, genkwanin, luteoloside, vicenin 2, rutin hydrate M-OH2, chrysin, α-cyano-4-hydroxycinnamic acid, gentisic acid, afzelin, quercetin, schaftoside, and apigenin 7-glucoside. In WSP, the following phenolic acids were identified: apigenin 7-glucoside (11.54 μg/kg), schaftoside (67.06 μg/kg), quercetin (75.72 μg/kg), afzelin (98.02 μg/kg), gentisic acid (101.54 μg/kg), α-cyano-4-hydroxycinnamic acid (114.19 μg/kg), chrysin (142.5 μg/kg), rutin hydrate M-OH2 (150.88 μg/kg), vicenin 2 (193.2 μg/kg), luteoloside (222.42 μg/kg), genkwanin (247.31 μg/kg), arbutin (309.37 μg/kg), isoorientin (796.28 μg/kg), orientin (856.95 μg/kg), benzoic acid (1443.51 μg/kg), caffeic acid (1,614.94 μg/kg), apigenin (3,103.2 μg/kg), 3,4-dihydroxyphenylacetic acid (3584.15 μg/kg), vanillin (4539.07 μg/kg), ferulic acid (5039.18 μg/kg), L-ascorbic acid (5352.55 μg/kg), rosmarinic acid (6464.71 μg/kg), liquiritigenin (7653.22 μg/kg), and 3-(4-hydroxyphenyl)propionic acid (7648.14 μg/kg), and narirutin (20738.74 μg/kg).

A quantitative analysis of watermelon rinds revealed the presence of various phenolic compounds. Among these, 4-hydroxybenzoic acid exhibited the highest concentration (958.3 μg/kg dw), followed closely by vanillin (851.8 μg/kg dw). Coumaric acid, on the other hand, was detected in the lowest quantities (8.8 μg/kg dw). (Al—Sayed & Ahmed, 2013). Catechol and vanillic acid were among the phenolic compounds identified in watermelon extracts. While hydrothermal treatment led to a decrease in malic acid content, it also resulted in the detection of several novel phenolic compounds. The primary phenolic compounds identified were catechol and its derivatives, including 4-methylcatechol, pyrogallol, and 1,2,4-benzenetriol (Kim et al., 2014). In the study where the phenolic and other compounds soluble in methanol extract of watermelon were investigated; Seventy-one phenolic compounds were detected and characterized in this study. Hydroxybenzoic and hydroxycinnamic acids are the predominant phenolic compounds (Abu-Reidah et al., 2013). The hydroxylated derivatives of catechol possess strong peroxynitrite scavenging capacity, as reported by Heijnen et al. (2001). The elevated levels of phenolic compounds in watermelon peel powder could have contributed to the increased antioxidant activity of the powder (Kim et al., 2014).

Antioxidant compounds such as 3,4-dihydroxybenzaldehyde, orientin, isoorientin, and quercetin were detected in watermelon peel and seed powders but were not present in the rind powder. The presence of these compounds may account for the higher antioxidant activity observed in the peel and seed powders. All powder samples contained vanillin and L-ascorbic acid. The phenolic compound, vanillic acid, is widely distributed in dietary sources and medicinal plants and is commonly used as a flavoring agent. Ascorbic acid, a well-known antioxidant, when combined with vanillic acid extracted from WBP, offers a sustainable resource for the food industry. A unique distribution of compounds was observed: syringic acid, rhoifolin, kaempferitrin, and astragalin were confined to the watermelon inner rind powder, whereas apigenin, apigenin 7-glucoside, genkwanin, schaftoside, afzelin, narirutin, liquiritin, rosmarinic acid, and arbutin were exclusively present in the WSP.

WBP have emerged as valuable sources of phenolic compounds. Extensive research has highlighted their potential therapeutic applications, encompassing anti-diabetic, antioxidant, antihypertensive, anti-inflammatory, anti-ulcer, antitumor, hypocholesterolemic, hepato-, nephro-, and neuroprotective effects, along with antibacterial properties (Zia et al., 2021). These findings underscore the importance of exploring the utilization of watermelon by-products in the development of novel functional foods. Such products can contribute significantly to sustainability within the food industry. Nevertheless, to comprehensively support the development of functional foods, nutraceuticals, and pharmaceuticals, additional research, especially clinical trials, is warranted.

4 | CONCLUSION

Despite the valuable nutrients they contain, the seeds, skins, and roots of fruits and vegetables are unfortunately discarded as waste. High levels of fat, protein, dietary fiber characterize the impressive nutrient profile of WPP, WRP and WSP, making them a valuable resource that should not be discarded. WBP must possess suitable physical properties for storage and transportation in powder form, enabling its use as a food additive. WSP has a lower water and oil retention capacity than WRP and WPP. Simultaneously, WSP exhibits a low bulk density and a medium fluidity. WPP and WRP have excellent fluidity, but the solubility of WRP (14.42%) is higher than the other samples. In this regard, it is more suitable for use in the food industry compared to WSP and WPP. We determined that WRP had a higher ash and protein content, WPP had a higher total dietary fibre content, and WSP had a higher protein and total fat content than the others. Mg and K contents were significantly higher than Fe and Na contents in all three powder types. WPP had the highest total phenolic matter and antioxidant activity, followed by WSP and WRP. Out of 47 kinds of phenolic acids tested in WBP, genistein emerged as the most dominant one. The present study's results indicate that WBP exhibits high nutritional and powder quality, making them suitable for use as functional food ingredients that can also yield economic benefits.

AUTHOR CONTRIBUTIONS

Sultan Acun: Writing—original draft; visualization; methodology; project administration; investigation; validation. **Hülya Gül**: Writing—review & editing; methodology; supervision; conceptualization. **Fadime Seyrekoğlu**: Writing, investigation.

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CONFLICT OF INTEREST STATEMENT

No potential conflict of interest was reported by the authors.

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