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Separation of free bran using electrostatic field system with electrically assisted flat PVC surface

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Abstract
The objective of this study was to investigate the possibility of separating free bran from bulgur using the triboelectric property of a flat PVC surface. The findings demonstrate that bran, which has an adverse impact on the physical appearance and quality of bulgur, can be effectively separated. It was established that the study offers a solution to the issue of bran. The use of a flat PVC surface, which can be defined as a flat inclined channel, represents a new technological development for bulgur production technology. The dimensions of the device were designed to be 4, 5 and 6 cm in width, 20, 40 and 60 cm in length, and with angles of 30, 35 and 40 degrees, respectively. A series of plates was fixed at the final point of the PVC surface in order to establish an electric field. To generate the electric field, one of the plates was subjected to a positive charge, while the other was treated with a negative charge. A variety of distances were observed between the plates, contingent upon the width of the tunnel. The flat PVC system proved to be an effective means of achieving the desired outcome. Consequently, a fine bulgur-bran mixture with an initial bran content of 5 g per 1000 g of bulgur was conducted through the system at a flow rate of 0.89 g/s. This resulted in a significant reduction in bran content from 5 g to approximately 2 g (60% reduction).
Keywords: Bulgur, Bran, Electrostatic separation, Electric field, PVC

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INTRODUCTION

Bulgur is a wheat product. The production process involves cooking, dehulling, cleaning, drying, milling, and, if necessary, polishing, before the final classification stage (Balci & Bayram, 2015). The size of bulgur can vary depending on the specific type or grade, and is typically classified into different size categories, ranging from fine to coarse. Fine bulgur is characterised by smaller grains, which are similar in size to couscous, while coarse bulgur has larger grains. Fine bulgur is a specific variety of bulgur, defined by its exceptionally small particle size, which is generally between 0.5 and 1.0 mm (Yılmaz, 2020). Due to a number of favourable characteristics, including low cost, high nutritional value, storability and ease of preparation, bulgur is an excellent food source. Additionally, it resists mould contamination, which makes it an ideal choice for those seeking a cost-effective, convenient, and nutritious food source (Bayram 2000).

Bulgur bran is a by-product of the bulgur production process. It is separated during the partial dehulling (debranning) stage and sold as animal feed at a significantly reduced price (Saka et al., 2020). Bulgur bran, a by-product of the agricultural industry, has significant potential as a renewable resource for the production of chemicals, materials, and biofuels (Kocabaş et al., 2021). Although bulgur bran is a nutritionally rich foodstuff, it is not a preferred food item for the end consumer. Bulgur bran has been the subject of various studies investigating its nutritional, chemical, and physical properties, as well as its potential applications. Research has shown that bulgur bran is a rich source of dietary fiber, bioactive compounds, and antioxidants (Saka et al., 2020; Tekin et al., 2021). It has been highlighted as a functional food due to its nutritional components, including B vitamins, minerals, and dietary fiber, as well as its low glycemic index (Tekin et al., 2021; Erbaş et al., 2016). Additionally, bulgur bran has been found to contain phytic acid, which varies based on particle size (Saka et al., 2020). Bran, a nutrient-rich cereal considered a staple food, is recognized for its many health benefits within a balanced and healthy diet. One of the main reasons for bran positive reputation is its excellent fiber content, which helps to support digestive health and general wellbeing.

Traditional separation methods such as fine mesh sieving, density difference, gravity separation and magnetic separation require more time and effort compared to modern techniques, they are highly respected for their ability to produce the highest quality bulgur with the least damage to the grains. However, it should be noted that bran cannot be completely separated from bulgur using classical separation methods, especially for fine bulgur due to its similar size (Kayıran & Bayram, 2024). The inability of conventional techniques to separate bulgur bran leads to the product forming a cohesive bond with the internal surface of the packaging, which creates the false impression of inferior quality.

In the field of particle technology, electrostatic separation represents a highly effective method for the separation of particles from granular mixtures (Matsusaka et al., 2010). This is due to the utilization of electrical forces which, in turn, allows for the separation to be carried out in a controlled and precise manner, thereby making it an attractive technique for various industrial applications (Hou et al., 2010). The application of electrostatic separation techniques has been investigated in the food industry, with particular emphasis on the separation of wheat grain and straw particles. Additionally, the technique has been employed for the recovery of food waste, thereby demonstrating its efficacy in the management of food waste and the recycling of valuable resources (Jafari et al., 2019; Lai et al., 2016).

Using an electrostatic field to separate bran from bulgur is a new technology to increase efficiency in the bulgur production process and separate these two components that are difficult to separate by the traditional method. It is of great importance to be aware of the nature of the constituents of bran and bulgur. In addition, the characteristics of the particles in question, specifically their size and shape, may also influence the separation process (Kayıran & Bayram, 2024). The particles themselves react in different ways to the electrostatic field depending on their inherent physical properties. (Zhu et al., 2023). The electrostatic separation process employs polyvinyl chloride (PVC). As a result of the triboelectric effect, electric charge is generated by electron transfer during friction or contact between materials (Wang et al., 2014). Polyvinyl chloride (PVC) is a synthetic polymer and a widely used material in the plastics industry (Flynn et al., 2017). PVC is recognised as a material that accumulates a negative electric charge. While other materials in contact with PVC show positive charge accumulation, PVC itself accumulates negative charge (Liu et al., 2021).

The purpose of these investigations is to utilize a flat PVC surface electrostatic system and electric field for the separation of bran from bulgur (see Figures 2 and 3). Additionally, the objective is to determine the capability of the PVC surface (flat inclined channel) in generating an electrostatic field and the success of the electric field.

MATERIALS AND METHODS

Sample Preparation

The experiments were conducted using samples of fine bulgur and bulgur bran provided by a local food company, (Tiryaki Agro Gıda San. ve Tic. A.Ş., Gaziantep, Turkey, in 2021). These samples are illustrated in Figure 1. Fine (köftelik) bulgur was processed according to Antep type method (Yousif et al., 2018). A series of analyses were performed on bulgur and bran samples, including moisture, protein, ash content and colour.

Both components (bulgur and bran) were sieved before the samples were prepared to contain 5 g/1000 g bulgur bran according to industry data. While 0.5 mm bulgur was passed through the first sieve, bran was passed through a 2 mm sieve. Thus, the particle sizes for both inputs were brought to close dimensions.

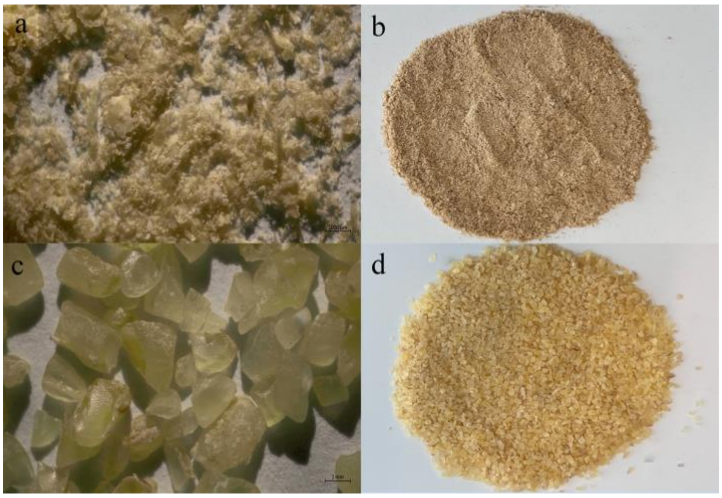

Figure 1. Images of (a) microscope images of bran, (b) bran, (c) fine bulgur [3x images] and (d) fine bulgur [magnification 300 dpi, scale 1000 micrometer.

Determination of protein content

Protein analysis was conducted in accordance with the Kjeldahl method (AOAC 1990) to determine the percentage of protein in the sample, expressed in grams per gram (g/g) on a dry basis. A conversion factor of 6.25 was employed for this calculation.

Determination of colour

The colour values (L*, a*, b* and YI) were determined utilizing a Hunter Lab Colourimeter (Colourflex, USA). The Hunter scale is employed to quantify lightness (luminosity) via the L parameter, which ranges from white to black, as perceived by the human eye. The a-value quantifies the degree of redness, whereas the b-value assesses the intensity of yellowness (positive values), greyness (zero values), and blueness (negative values). The YI, or yellowness index, is a measure of the relative intensity of yellow tones in a given colour.

Determination of ash content

Ash content was measured according to AOAC (1990) methods.

Electrostatic seperation experiment with electric field

The design of the system incorporates a PVC surface that is as flat as possible to generate an electrostatic and electric field (Figures 3). To this end, fine bulgur (5 g/1000 g bulgur bran) was passed through the PVC surface at various widths (4, 5 and 6 cm), lengths (20, 40 and 60 cm) and angles (30, 35 and 40°), respectively.

As a result of trial and error tests in a laboratory environment, it was determined that Bulgur and bulgur bran exhibit positive triboelectric properties. By utilizing the negative triboelectric properties of PVC material, an electrostatic field was created by friction.

Polyvinyl chloride (PVC) is a polymer that is employed in a multitude of applications, including cables, thermoplastics, and polymerized vinyl chloride products (Thabet, 2024). The material is produced through the polymerization of vinyl chloride and is renowned for its versatility and durability. Due to its cost-effectiveness and resistance to chemicals, weathering and impact, PVC is one of the most commonly used materials (Andrady and Neal, 2009).

PVC compound is observed to accumulate a net negative electric charge through a phenomenon known as the triboelectric effect. This effect refers to an electron transfer process occurring between materials that are subjected to either contact or friction (Miura et al., 2014).

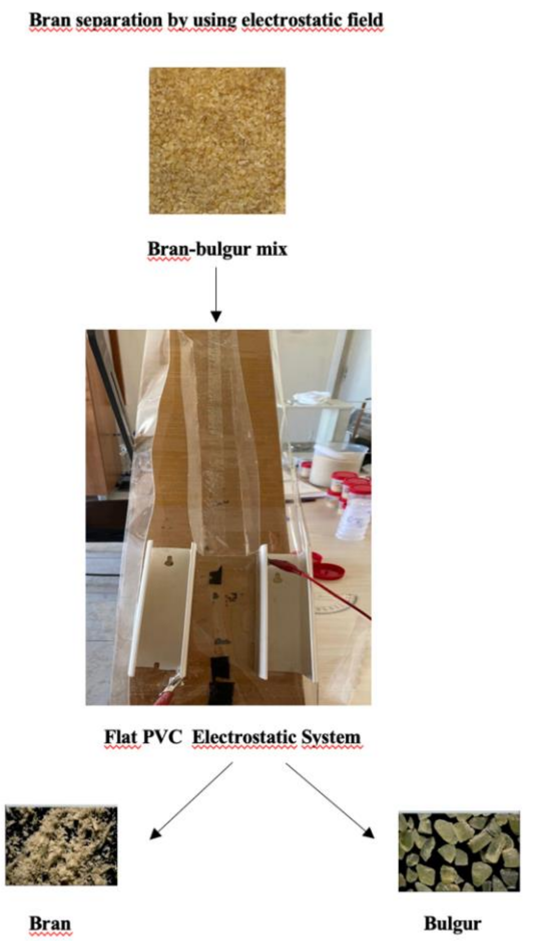

Figure 2. Schematic diagram of the electrostatic separation of system.

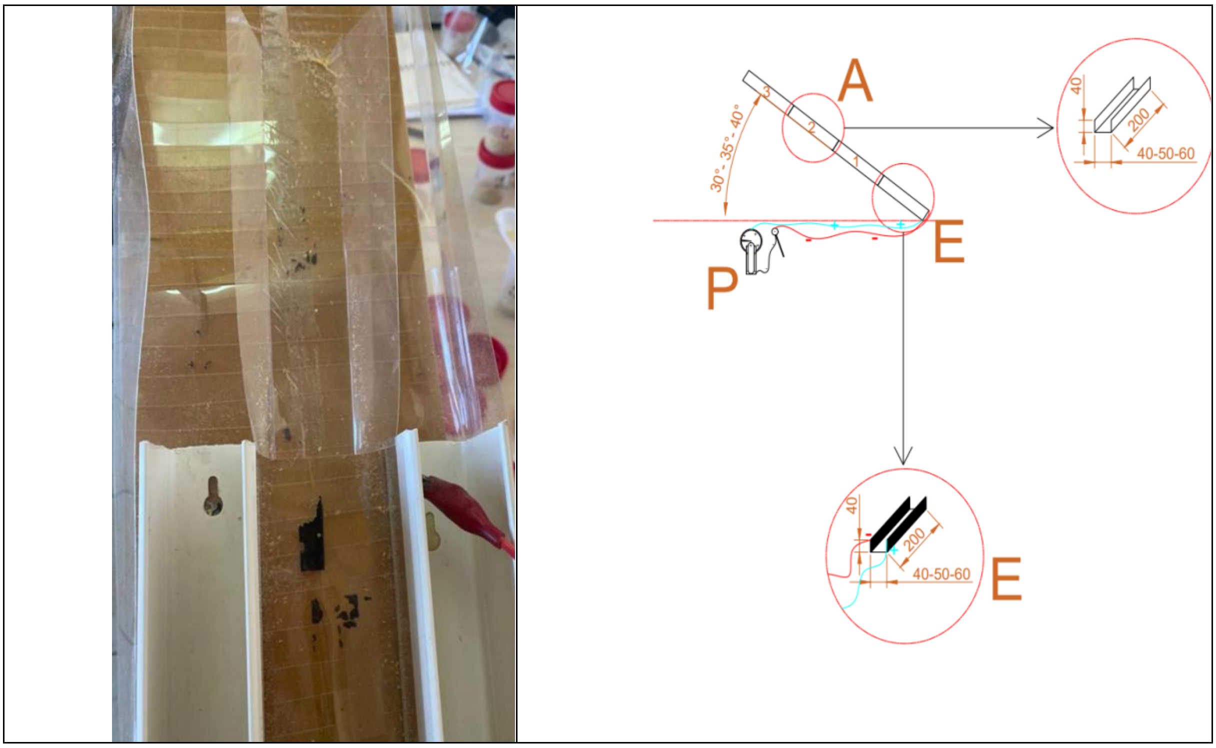

Figure 3. Flat PVC surface systems.

It was observed that how much bulgur bran could be separated by passing the bulgur through the devices prepared from PVC material and the electric field with a certain mass flow rate.

Figure 2 and figure 3 show that the system design of flat PVC surfaces and electric field. The flat system was prepared with PVC assemblies with the widths of 4, 5 and 6 cm and the lengths of 20, 40 and 60 cm, respectively. Different angles were designed therefore the angle of the system was 30, 35 and 40°. Plates are placed to create an electric field where the PVC surface ends. To create the electric field, one of the plates was charged with a positive and the other with a negative charge. The distance between the plates was varied as the tunnel distances (4, 5 and 6 cm). The electric field was calculated according to the following formulation (Fitzpatrick, 2010) (Eqn. 1).

$$E = \frac{V}{d}$$

In this formula, E (V/m) represents the electric field, V (V) refers to the potential difference between the two plates, and d (m) defines the distance between the two plates. (Fitzpatrick, 2010). According to this formula, the electric field for 4, 5 and 6 cm width is 5500 kv, 4400 kv and 3666 kv respectively.

Van de Graaff generator was also used as the power source for the electric field. The generator works on the principle of generating high voltages from a current-limited source (Lee et al., 2017). This generator consists of an isolating belt driven by an electric motor and stretched between two roller (Sessler &Wilson, 2014). The maximum voltage capacity of the generator depends on the diameter of the generator sphere. The voltage collected by the generator can be calculated approximately over the maximum value. For a 25 cm diameter sphere, the theoretical voltage collected by the generator is based on 220kv (Ege et. al., 2014). In addition, in order to accumulate sufficient potential voltage, the generator was waited for 5 minutes after the generator started and then the bulgur flow was realized.

Characterization by infrared spectroscopy (FT-IR)

The aim was to establish the impact of groupings within the chemical composition on the electrostatic field. For this purpose, Fourier Transform Infrared Spectroscopy (FT-IR) was used, utilizing a PerkinElmer Spectrum 100 FT-IR spectrometer (PerkinElmer Inc., Waltham, MA, USA). The procedure was carried out on a variety of samples, including bran, fine bulgur and bulgur–bran blends, with 5 g of bran and 1,000 g of bulgur used for each blend. Fourier transform infrared (FTIR) spectroscopy was used to obtain mid-infrared spectra with four scans, 4 cm-1 resolution and 4 scans using the Spectrum 10 Software (PerkinElmer Inc., Waltham, MA, USA). As a result, the spectra could be collected in the range of 4000-650 cm-1. Four separate transmittance spectra were obtained for each individual sample, with the ground sample positioned at the center of the diamond crystal on each occasion.

Statistical analysis

The analysis of variance (ANOVA) was conducted according to standard procedure to evaluate the impact of the system on ΔX, L, and α. The Pearson coefficient was utilized to ascertain the statistically significant correlation, with a level of significance set at $P \leq 0.05$. The statistical analyses were performed using SPSS software (SPSS Inc., Chicago, IL, USA). The measurements were conducted in duplicate, and the experiments were replicated.

RESULTS AND DISCUSSION

The moisture content of the bulgur sample was found to be 10.50% (db), and the bran sample exhibited a moisture content of 10.00% (db). Bulgur exhibited a protein content of 10.26% (dry basis), whereas bran exhibited a significantly higher protein content of 14.22% (dry basis). It was determined that the ash content of the bulgur was 0.89% (d.b.), while the ash content of the bran was 3.80% (d.b.). To ensure an accurate assessment of the system's efficiency, it is essential to consider the changes in both the ash content and the bran yield. Concurrently, the colour values were as follows: The following values were obtained for the bulgur sample: L*: 70.62, a*: 4.86, b*: 25.99 and YI: 57.56. The values for the bran sample were as follows: L*: 64.18, a*: 6.34, b*: 38.39 and YI: 81.07. The samples were subjected to a process involving a flat PVC surface. The bulgur-bran mixture displaying the identified characteristics was then subjected to the same process, with the efficiency of the system being interpreted based on the results obtained for the bran (GB). This involved weighing the amount of bran that had been separated by the electrostatic field and analysing the ash content. The term "gained bran (GB) refers to the amount of bran that was successfully removed from the system with the assistance of the PVC surface.

The impact of various variables, including surface width (ΔX), length (L), and angle (α), on the separation of bran from bulgur was examined using a PVC surface with highly negative triboelectric properties.

A statistical analysis revealed a significant difference ($P \leq 0.05$) in the amount of bran gained according to the width (ΔX) of the flat PVC with an electric field system. Understanding the efficiency of the system requires consideration of changes in both the amount of ash and gained bran. Therefore, both quatities were measured. The bran gain results showed that there were significant differences ($P \leq 0.05$) in bran separation between flat PVC surfaces. The quantity of bran obtained from PVC samples with widths of 4 cm, 5 cm, and 6 cm was found to be 0.10 ± 0.02 g, 0.09 ± 0.03 g, and 0.03 ± 0.00 g, respectively. A comparison between the groups indicated that the 4 cm width PVC samples yielded a higher quantity of bran than the other widths. The results indicated that significant differences ($P \leq 0.05$) existed between the length (L), (ΔX* L) and (ΔX* α) variables. The observed differences in the quantities of bran acquired according to the variables α, (L* α), and (ΔX* L* α) were not statistically significant, as indicated by ($P \geq 0.05$). The narrowest channel width and length proved optimal for the separation of the bran from the bulgur. The highest bran separation was observed at tunnel widths of 4 cm, lengths of 20 cm and system angles of 40 degrees. The ash values of the flat PVC system are in alignment with the bran values obtained. Duncan's Multiple test analysis, as illustrated in Table 1, revealed that the channel width and length were identified as crucial variables influencing the separation of bran from bulgur.

The structural characteristics of bulgur, bran and bulgur–bran mixtures were examined using FT-IR transmission spectroscopy, with the samples prepared by passing them through different angle assemblies. The figures demonstrate the positioning of bulgur, bran and the angle of the system, as illustrated in Figure 4. The peaks observed at approximately 3278 cm-1 are linked to the O-H stretching region of hydrogen bonds, which are formed between aliphatic and aromatic groups of alcohol and water. It may be inferred from the peak at 2925 cm^{-1}that a C-H linkage is involved in an aldehyde. It appears that these peaks have a cellulose and starch origin (Berthomieu, C., et al., 2009). The presence of a peak at 1635 cm-1, assigned to the Amide I functional group, was verified. It can be reasonably inferred that the peaks observed at 1365 and 1148 cm^{-1} are indicative of deformation of the C-H bond, thereby suggesting the presence of cellulose structures. In addition, the deformation of a range of polysaccharides is evident in the peaks observed at 1077 cm^{-1}. A maximum value of 994 cm^{-1} is suggestive of a C-OH bending mode (Amir et al., 2013; Bledzki et al., 2010). The FTIR spectra provide confirmation that no significant structural alteration took place during the separation of bulgur from bran using PVC surfaces. Additionally, the data indicate that the composition of bulgur and bran is chemically similar. The FTIR spectra confirm that no major structural changes occur during the separation of bran from bulgur. Therefore, the FTIR spectra evidence that the process of bran separation causes no structural alteration to the bulgur.

Application of the Systems in Industry

The traditional method of sieving is carried out after the milling process, where the bulgur is ground to various particle sizes. This step is very important as it allows the separation of finer bulgur particles from coarser ones that can be used for different culinary applications. In the sieving process, a series of sieves or screens with different pore sizes are typically used to achieve the desired granulation (Erbaş et al., 2016). Additionally, the sieving process can also help in the removal of any remaining bran particles, thereby enhancing the overall quality and appearance of the bulgur (Yağcı et al., 2022).

Although some traditional separation systems are used to separate the bulgur bran after the grinding process in the bulgur production, the separation of bulgur and bran is not completely efficient. Unseparated bran still creates problems in the sector, today. The bran adhering to the inner surface of the package causes the fine bulgur to look different and creates problems for the end-consumer. The process in the present study to solve the problem in the sector was designed as an improvement. The system mentioned in the study can be added to the process before packaging.

Before packaging, the fine bulgur can be separated from the bulgur bran using a PVC surface that gives electrons by friction. The bran remaining on the system surface can be designed to be removed from the process in two ways. The system surface can be completely covered with bran after a certain amount of bulgur passage, and the PVC surface must be cleaned periodically by using moving brush and/or negative pneumatic (vacuum) for efficient operation of the system.

Table 1 The results of the flat PVC electrostatic system with using electric field.

Parameters			Elestrostatic systems with electric field Flat PVC System	
ΔX (cm)	L (cm)	α (°)	Gained bran (g)	Ash content (%, g/g, d.b.)
4	20	30	0,11±0,00 ^{h,i,j,k}	3,05±0,13 ^{b,c,d,e}
		35	0,12±0,00 ^{k}	2,99±0,09 ^{b}
		40	0,13±0,01 ^{k}	2,75±0,13 ^{a}
	40	30	0,09±0,00 ^{f,g,h,i,j}	3,23±0,17 ^{d,e,f,g}
		35	0,08±0,01 ^{e,f,g,h}	3,30±0,08 ^{e,f,g,h,i}
		40	0,09±0,02 ^{f,g,h,i,j}	3,29±0,10 ^{e,f,g,h}
	60	30	0,06±0,00 ^{b,c,d,e,f}	3,45±0,17 ^{h,i,j,k,l}
		35	0,09±0,00 ^{f,g,h,i,j}	3,20±0,22 ^{c,d,e,f,g}
		40	0,09±0,01 ^{e,f,g,h,i,}	3,23±0,17 ^{d,e,f,g}
5	20	30	0,10±0,08 ^{g,h,i,j,k}	3,09±0,09 ^{b,c,d,e}
		35	0,11±0,03 ^{i,j,k}	3,00±0,08 ^{b,c}
		40	0,09±0,01 ^{f,g,h,i,j}	3,25±0,17 ^{d,e,f,g,h}
	40	30	0,12±0,02 ^{j,k}	3,05±0,13 ^{b,c,d,}
		35	0,09±0,02 ^{f,g,h,i,j}	3,15±0,24 ^{b,c,d,e,f}
		40	0,08±0,01 ^{d,e,f,g}	3,35±0,06 ^{f,g,h,i,j}
	60	30	0,07±0,00 ^{c,d,e,f,g}	3,40±0,08 ^{g,h,i,j,k}
		35	0,06±0,00 ^{a,b,c,d,e}	3,50±0,08 ^{i,j,k,l,m}
		40	0,05±0,00 ^{a,b,c,d}	3,53±0,25 ^{i,j,k,l,m,n}
6	20	30	0,05±0,00 ^{a,b,c,d}	3,55±0,06 ^{i,j,k,l,m,n}
		35	0,05±0,00 ^{a,b,c}	3,60±0,12 ^{k,l,m,n,o}
		40	0,04±0,00 ^{a,b}	3,60±0,08 ^{k,l,m,n,o}
	40	30	0,04±0,00 ^{a,b}	3,73±0,10 ^{n,o}
		35	0,04±0,00 ^{a,b}	3,63±0,17 ^{l,m,n,o}
		40	0,03±0,01 ^{a}	3,70±0,08 ^{m,n,o}
	60	30	0,03±0,00 ^{a}	3,78±0,05 ^{o}
		35	0,03±0,00 ^{a}	3,78±0,05 ^{o}
		40	0,03±0,00 ^{a}	3,78±0,05 ^{o}

The results were also correlated using Pearson's correlation coefficient. In the flat PVC system, a significant negative correlation (-0.692) between ΔX and GB was observed and negative correlation (-0.358) between ΔX and length, as shown Table 2.

Table 2. Pearson correlation of flat PVC electrostatic system with using electric field.

		ΔX	L	α	GB	ASH%
ΔX	Pearson Correlation	1	0.000	0.000	-0.692*	0.704*
	Sig. (2-tailed)		1000	1000	.000	.000
	N	108	108	108	108	108
L	Pearson Correlation	0.000	1	0.0000	-0.358*	0.416*
	Sig. (2-tailed)	1.000		1000	0.000	0.000
	N	108	108	108	108	108
α	Pearson Correlation	0.000	0.000	1	-0.053	0.023
	Sig. (2-tailed)	1.000	1.000		0.587	0.816
	N	108	108	108	108	108
GB	Pearson Correlation	-0.692*	-0.358*	-0.053	1	-0.803*
	Sig. (2-tailed)	0.000	0.000	0.587		0.000
	N	108	108	108	108	108
ASH%	Pearson Correlation	0.704*	0.416*	0.023	-0.803*	1
	Sig. (2-tailed)	0.000	0.000	0.816	0.000	
	N	108	108	108	108	108

*: Correlation is significant at the 0.05 level (2-tailed).
GB: Gained bran (g), ΔX: width of channel (cm), L: length of channel (cm), α: angle of channel (°), Ash%: Ash content

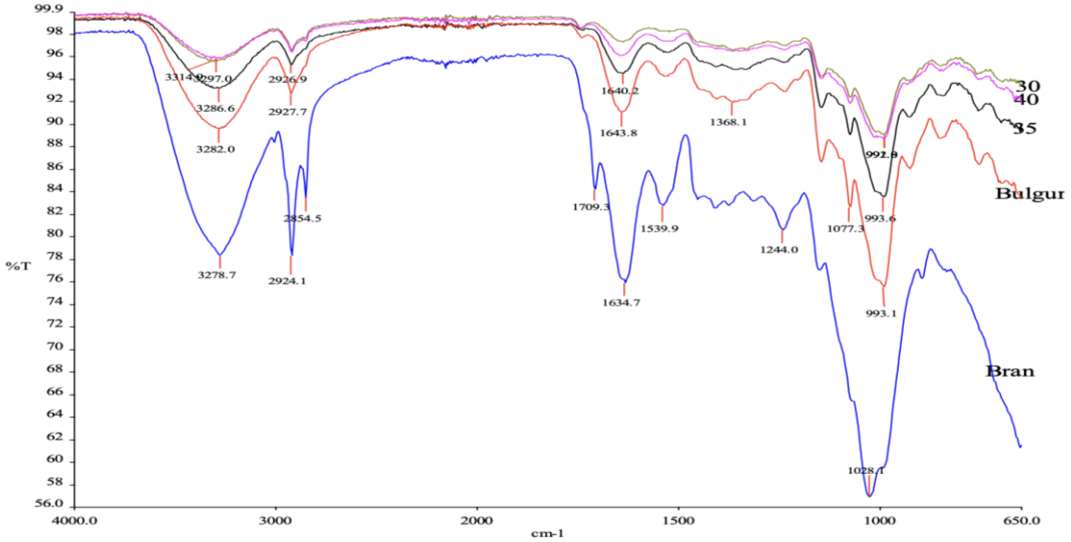

Figure 4 F-TIR Spectra of Bulgur, bran and angle of the system were shown. F-TIR Spectra of flat PVC with electric field system, ΔX 4 cm, L 20 cm.

CONCLUSION

The research has major implications for the food industry as it demonstrates the feasibility of a novel approach to cereal processing, including the production of bulgur. The implementation of sustainable practices is of critical importance for the development of optimal nutrient profiles and product quality. The use of electrostatic field and electric field separation of powder components that cannot be separated by conventional methods represents a sustainable method that can be used in this context.

Consequently, there is a clear potential for the utilization of both an electrostatic field and electric field to represent a promising methodology for the separation of the bran component of bulgur. To ensure the successful separation of the bran component of bulgur, it is of paramount importance to carefully consider and evaluate a number of factors. Furthermore, the intensity of the electrostatic field, the electric field, the properties of the particles and the precise configuration are also factors that must be taken into account. Further improvement may be achieved through experimentation and optimisation, resulting in enhanced outcomes. The findings of this study will prove invaluable in investigating the impact of the separation of cereal products using electrostatic and electric fields on product quality and production efficiency. The advancement of this and analogous methodologies will facilitate the production of superior-quality products. Furthermore, the findings of this study contribute to the scientific literature by providing data obtained from experimental studies on the use of electrostatic and electric fields in the separation of cereal products, as well as methods to improve the quality of cereal products in industry.

In addition to all the advantages, the flow must be stopped in order to remove the bran accumulated in the system. For this disadvantageous situation, alternatives to the foreseen methods can be developed. It may constitute a basis for further research.

Compliance with Ethical Standards

Peer-review

Externally peer-reviewed.

Conflict of Interests

The authors have no conflicts of interest to declare.

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