*Bulgarian Chemical Communications, Volume 57, Special Issue D (pp. 48-53) 2025 DOI:10.34049/bcc.57.D.MAEP1*

# Investigation of water absorption index, water solubility index and color changes of extrudates from corn semolina enriched with watermelon seed flour

S. Kodinova[1], N. Toshkov[1*], A. Simitchiev[2], M. Nikolova[3], A. Slavov[3], B. Bozadjiev[4], P. Karova[5]

[1]*Department of Process Engineering, Faculty of Engineering, University of Food Technologies, 4002 Plovdiv, Bulgaria*
[2]*Department of Preservation and Refrigeration Technology, Faculty of Technology, University of Food Technologies, 4002 Plovdiv, Bulgaria*
[3]*Department of Engineering Ecology, Faculty of Economics, University of Food Technologies, 4002 Plovdiv, Bulgaria*
[4]*Department of Technology of Grain, Fodder, Bakery and Confectionary Products, Faculty of Technology, University of Food Technologies, 4002 Plovdiv, Bulgaria*
[5]*Department of Microbiology and Biotechnology, Faculty of Technology, University of Food Technologies, 4002 Plovdiv, Bulgaria (Student)*

Revised: September 09, 2025

A full factorial $2^3$ experimental design was employed to investigate the effect of watermelon seed flour content (3 % and 10 %), temperature of the matrix (160 °C and 180 °C) and moisture content (14 % and 18 %) on the water absorption index (*WAI*), water solubility index (*WSI*) and color characteristics. Extrusion was performed using a single-screw Brabender 20 DN extruder. The *WAI* ranged from 5.54 g/g to 7.26 g/g, *WSI* varied between 11.68 % and 17.03 % and the color difference ($\Delta E$) ranged from 8.22 to 14.55. Statistical analysis indicated that the *WAI* increases with rising of moisture content, while the *WSI* decreases. Furthermore, increasing the watermelon seed flour content from 3 % to 10 % resulted in a decrease in *WAI* and an increase in *WSI*.

**Keywords:** extrusion, corn semolina, watermelon seed flour, color, water absorption index, water solubility index
**Abbreviations:** *WAI* – water absorption index; *WSI* – water solubility index; WSF – watermelon seed flour

## INTRODUCTION

In recent years, there has been growing interest in the consumption of functional food products, primarily driven by increased consumer awareness of the role of diet in maintaining and enhancing health [1, 2]. The market demands the development of novel enriched food products with diverse shapes, compositions, flavors, textures, and competitive prices that meet consumers' nutritional requirements and provide valuable bioactive compounds beneficial to health [3].

Currently, there is an emerging focus on the valorization of food products and nutrient-rich waste streams. Such approaches contribute to the production of novel food products with improved qualities [4]. Watermelon seeds, often considered waste, can be utilized to develop extruded products with significant nutrient content [4, 5]. Watermelon seeds are an excellent source of fats, proteins, minerals including magnesium, potassium, phosphorus, iron, zinc, sodium, calcium, and copper, as well as vitamins (A and B groups) and various phytochemical compounds [6].

Extrusion is a modern, specialized technological process employed in the manufacture of diverse products such as grain-based snacks, meat substitutes, pasta, confectionery, baby food, and pet food, which are distinguished by superior quality and composition compared to those produced using traditional methods [1, 7]. This process enables the production of food products with controlled composition, distinctive shapes, and enhanced flavor.

The water absorption index and water solubility index serve as key indicators to assess the functional properties of extrudates and predict their behavior during storage. These indices are influenced by two primary groups of factors: those related to the raw material properties and those associated with extrusion process conditions [8]. Achieving food products with desired characteristics necessitates a thorough understanding of the extrusion process [7].

The present study aimed to investigate the water absorption index, water solubility index, and color changes of extrudates produced from corn semolina enriched with watermelon seed flour.

* To whom all correspondence should be sent:
E-mail: *nesho.t@abv.bg*

a b

**Fig. 1.** Watermelon seeds (a) and watermelon seed flour (b)

## EXPERIMENTAL

### *Materials*

*Watermelon seed flour (WSF).* Watermelon seeds (*Citrullus vulgaris*) were collected from fresh ripe fruits purchased at the provincial market in Plovdiv, Bulgaria. The seeds were ground into a fine powder using an electric blender (Nutribullet Model OC22300058, 600 W, China) (Fig. 1). The resultant powder was then passed through a sieve with 1 mm mesh size to obtain flour with an average particle diameter of 0.68 mm, which was subsequently packaged for further use. The average chemical composition of the WSF was 8 % moisture, 25.4 % fat, and 3 % ash.

*Corn semolina.* The experiment utilized 'Familex' corn semolina, with a moisture content of 13 %, sourced from the local market in Plovdiv, Bulgaria. The WSF and corn semolina were mixed in the specified proportions, and water was added to achieve the desired moisture content (Table 1).

### *Extrusion*

A single-screw laboratory extruder, Brabender 20 DN (Duisburg, Germany) [9], was employed for extrusion under varying process parameters (Table 1). The extrusion was conducted under fixed conditions, including nozzle diameter of 3 mm, screw compression ratio of 3:1, extruder screw speed of 200 rpm, feeding screw speed of 30 rpm, and temperatures set at 140 °C and 150 °C for the first and second extruder zones, respectively.

### *Statistical analysis*

A full factorial design ($N = 2^3$), was applied during the processing. The independent variables were watermelon seed flour content ($X_1$), temperature of the matrix ($X_2$), and moisture content ($X_3$). The experimental design is presented in Table 1. The variation levels for each factor were selected based on literature data and preliminary studies [10, 11]. Each experimental condition was replicated three times.

**Table 1.** Design with natural and coded values of factors

| № | Natural values | | | Coded values | | |
|---|---|---|---|---|---|---|
| | Watermelon seed flour content, % | Temp. of the matrix, °C | Moisture content, % | $X_1$ | $X_2$ | $X_3$ |
| 1 | 3 | 160 | 14 | -1 | -1 | -1 |
| 2 | 3 | 180 | 14 | -1 | +1 | -1 |
| 3 | 10 | 160 | 14 | +1 | -1 | -1 |
| 4 | 3 | 160 | 18 | -1 | -1 | +1 |
| 5 | 3 | 180 | 18 | -1 | +1 | +1 |
| 6 | 10 | 160 | 18 | +1 | -1 | +1 |
| 7 | 10 | 180 | 14 | +1 | +1 | -1 |
| 8 | 10 | 180 | 18 | +1 | +1 | +1 |

A linear regression model including interactions between factors, was employed to describe the relationships using coded variables:

$$y = b_0 + \sum_{i=1}^{n} b_i X_i + \sum_{i=1}^{n} \sum_{j=1}^{n} b_{ij} X_i X_j \quad (1)$$

where $b_o$ - free coefficient;

$b_i$ - coefficient of linear effect;

$b_{ij}$ - coefficient of interaction.

The critical value of Fisher's criterion ($F_c$) was used to evaluate the adequacy of the models. All statistical analyses were performed using the Statgraphics XVII Centurion trial version software.

### *WAI and WSI analysis*

The water absorption index (*WAI*) and water solubility index (*WSI*) were determined following the AACC Method 56-20 [12]. The extrudate was ground, and a 0.2 g sample was mixed with 5 cm³ of distilled water. The mixture was suspended in water at 30 °C for 30 min with gentle agitation. Subsequently, it was centrifuged using a CH 90-2A (China) centrifuge at 3000 rpm for 20 min. The supernatant was decanted into a pre-weighed evaporating dish and dried at 105 °C until a constant weight was obtained. After cooling, the dried sample was weighed. Threefold repetition was used to obtain all experimental results.

The *WAI* was calculated as follows:

$$WAI = \frac{m_g}{m_s}, \text{ g/g} \quad (2)$$

The *WSI* was defined as:

$$WSI = \frac{m_{ds}}{m_s} . 100, \% \quad (3)$$

where $m_g$ – weight of sediment, g;

$m_s$ – weight mass of sample, g;

$m_{ds}$ – weight of dry solids after evaporation of the supernatant, g.

*Color analysis*

The extrudates were ground using a laboratory grinder to a particle size of 200 µm, after which their color was measured using an NS800 spectrophotometer (3nh, China) based on the CIE L*a*b color system. In this system, $L$ represents lightness ($L$ = 0 corresponds to black and $L$ = 100 to white), $+a$ indicates red, $-a$ green, $+b$ yellow, and $-b$ blue. The color difference ($\Delta E$) was calculated using the following formula:

$$\Delta \mathrm{E} = \sqrt{(L - L_0)^2 + (a - a_0)^2 + (b - b_0)^2} \quad (4)$$

where $L$, $a$ and $b$ - values of the extruded samples; $L_o$, $a_o$ and $b_o$ - values of the non-extruded mixtures (Table 2).

Threefold repetition was used to obtain all experimental results.

**Table 2.** Color parameters of non-extruded mixtures

| WSF content (%) | $L_0$ | $a_0$ | $b_0$ |
|---|---|---|---|
| 3 | 79.12 | 5.96 | 33.85 |
| 10 | 77.02 | 5.90 | 33.86 |

RESULTS AND DISCUSSION

Water absorption and solubility index are some of the important indicators of the quality and behavior of extrudates during processing and storage. Table 3 presents the mean values and standard deviations of the water absorption index (*WAI*) and water solubility index (*WSI*) as influenced by the three factors studied. The results indicate that *WAI* ranges from 5.54 g/g to 7.26 g/g. The maximum *WSI* value of 17.03 % is obtained at watermelon seed flour content 10 %, temperature of the matrix 160 ºC, moisture content 18 % and the lowest value of 11.68 % at watermelon seed flour content 3 %, temperature of the matrix 180 ºC, moisture content 18 %. As can be seen from the results, the increase in WSF content from 3 % to 10 % leads to a higher value of *WSI,* which may be due to the fact that the higher concentration of watermelon seeds enhances the solubility of the matrix in water and provides more soluble compounds or increases the surface area for water interaction. Seth *et al.* [13] examined the influence of feed composition (10 % – 40 %), moisture content (12 % - 24 %) and extrusion temperature (100 °C – 140 °C) on extrudate characteristics of yam-corn-rice based snack food and reported that water absorption index increased significantly with the increase in all examined variables. Eftekhariyazdi *et al.* [14] investigated the combined effect of the pumpkin-flour ratio (25 % – 75 %), feed moisture content (14 % – 22 %) and barrel screw speed (120 rpm – 180 rpm) on the physical attributes of extrudates and found strong positive effect of moisture content on the *WAI*. The increase in the pumpkin-flour ratio from 25 % to 75 % increases the values of *WSI*.

**Table 3.** Results for *WAI* and *WSI*

| № | *WAI*, g/g | *WSI*, % |
|---|---|---|
| 1 | 5.54 ± 0.08 | 13.10 ± 0.08 |
| 2 | 6.59 ± 0.22 | 12.78 ± 0.10 |
| 3 | 6.00 ± 0.02 | 16.84 ± 0.20 |
| 4 | 7.26 ± 0.23 | 11.98 ± 0.13 |
| 5 | 6.50 ± 0.13 | 11.68 ± 0.27 |
| 6 | 6.57 ± 0.19 | 17.03 ± 0.10 |
| 7 | 6.01 ± 0.05 | 15.26 ± 0.09 |
| 8 | 6.73 ± 0.17 | 15.09 ± 0.14 |

The Pareto chart (Fig. 2A) illustrates that, with respect to *WAI*, the factors moisture content ($X_3$), WSF content ($X_1$), as well as the interactions between factors ($X_2X_3$) and ($X_1X_2X_3$), are statistically significant. The greatest effect is attributed to the moisture content ($X_3$), followed by the interactions ($X_1X_2X_3$) and ($X_2X_3$), and subsequently by watermelon seed flour content ($X_1$). Regarding *WSI* (Fig. 2B), the results indicate that the single factors ($X_1$), ($X_2$), and ($X_3$), together with the interactions ($X_1X_2$) and ($X_1X_3$), are significant. The most pronounced positive effect on *WSI* is exerted by the watermelon seed flour content ($X_1$), followed by the negative effects of temperature of the matrix ($X_2$) and moisture content ($X_3$).

The adequate linear mathematical models shown below, comprising statistically significant coefficients, were developed at a significance level of 0.05:

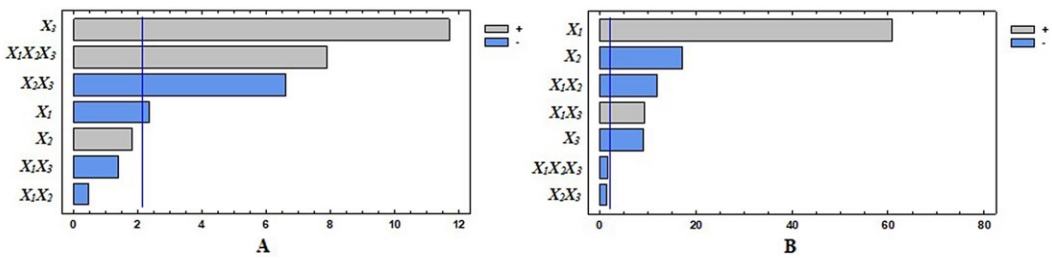


**Fig. 2.** Pareto charts for *WAI* (A) and *WSI* (B)

$$WAI = 6.399 - 0.073X_1 + 0.3654X_3 - 0.2063X_2X_3 + 0.2463X_1X_2X_3 \quad (5)$$
$R^2 = 92.81$ %   $F = 0.24 < F_c = 3.2$

$$WSI = 14.22 + 1.8358X_1 - 0.5167X_2 - 0.2742X_3 - 0.3625X_1X_2 + 0.28X_1X_3 \quad (6)$$
$R^2 = 99.57$ %   $F = 0.39 < F_c = 3.6$

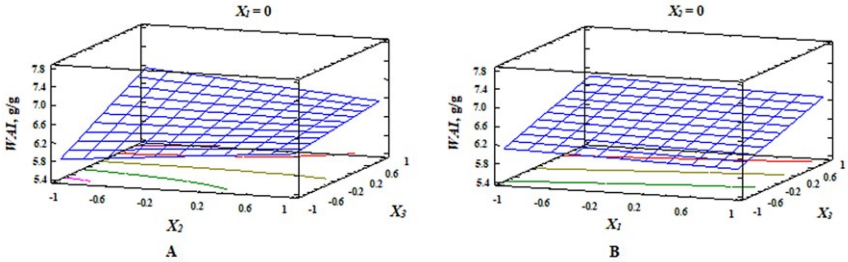


**Fig. 3.** Response surface of *WAI*, depending on: **A.** temperature of the matrix ($X_2$) and moisture content ($X_3$); **B.** watermelon seed flour content ($X_1$) and moisture content ($X_3$)

The adequacy test of the obtained models for *WAI* and *WSI* in coded form shows that the calculated value of the Fisher criterion is smaller than its critical value. The determination coefficient value for both parameters is above 92.81 %.

The combined effect of matrix temperature ($X_2$) and moisture content ($X_3$) is illustrated in Fig. 3A. These two parameters are the principal variables significantly affecting the *WAI*, as they are directly associated with starch gelatinization. The highest *WAI* value is attained at a lower level of temperature of the matrix and a higher level of moisture content, whereas the lowest value is observed when both factors are at lower levels (Fig. 3A). *WAI* increases 1.50 times when the moisture content rises from 14 % to 18 %, under otherwise identical conditions.

This indicates that higher moisture content enhances water absorption capacity, which may be attributed to the increased ability of extrudates to absorb water – potentially influencing the texture and overall quality of the final product. This trend is relevant for optimizing formulation and processing parameters to achieve the desired water absorption characteristics in food products. Comparable results were observed in our previous study involving the extrusion of corn semolina and cocoa bean shells [15]. It is evident that most of the variation in *WAI* is primarily governed by moisture content, rather than matrix temperature.

The influence of *WSF* content ($X_1$) and moisture content ($X_3$) on the *WAI*, at constant temperature of the matrix ($X_2$), is presented in Fig. 3B. An increase in watermelon seed flour content results in a slight reduction in *WAI* at both the lower and upper levels of moisture content. In contrast, an increase in moisture content ($X_3$) induces a more pronounced effect on *WAI* when the *WSF* content ($X_1$) is at its lower level.

The effect of *WSF* content ($X_1$) and matrix temperature ($X_2$) on *WSI*, at a constant moisture content ($X_3$), is illustrated in Fig. 4A. The data clearly indicate that the factor ($X_1$) exerts a dominant influence compared to factor ($X_2$), probably due to the presence of components in the watermelon seed flour – such as soluble proteins and low molecular weight polysaccharides – which contribute to the increase in *WSI*. The highest *WSI* value is observed at a higher level of ($X_1$) and a lower level of ($X_2$). This may be attributed to enhanced starch gelatinization, dextrinization, and molecular degradation under elevated thermal conditions. Such structural modifications improve the solubility of starch and associated compounds, thereby resulting in increased *WSI* values.

The combined influence of matrix temperature ($X_2$) and moisture content ($X_3$) on *WSI* at a constant level of *WSF* content ($X_1$), is presented in Fig. 4B. The response surface appears nearly flat, suggesting that neither temperature of the matrix nor moisture content exerts a significant effect on *WSI* within the investigated range. This observation is corroborated by the standardized Pareto chart (Fig. 2B) and the coefficients obtained in eqn. 6.

The impact of *WSF* content ($X_1$) and moisture content ($X_3$) on the *WSI*, at a fixed temperature of the matrix ($X_2$), is illustrated in Fig. 4C. An increase in watermelon seed flour content results in a corresponding rise in *WSI*, likely attributable to the presence of components such as soluble proteins, simple sugars, and low-molecular-weight starch fragments, which enhance the solubility of the extrudates. Within the studied range, moisture content exerts minimal or no significant effect on *WSI*. The highest *WSI* value is recorded at the highest level of ($X_1$) and the lowest level of ($X_3$), whereas the lowest value occurs at the lowest level of ($X_1$) and the highest level of ($X_3$).

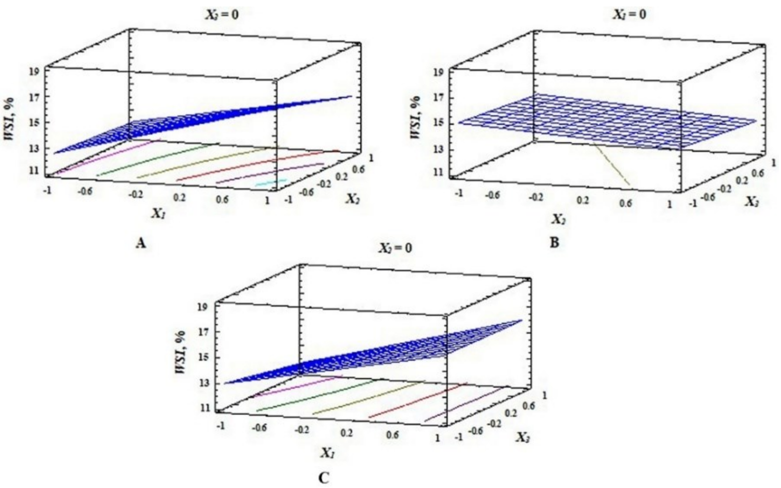


**Fig. 4.** Response surface of *WSI*, depending on: **A.** watermelon seed flour content ($X_1$) and temperature of the matrix ($X_2$); **B.** temperature of the matrix ($X_2$) and moisture content ($X_3$); **C.** watermelon seed flour content ($X_1$) and moisture content ($X_3$)

**Table 4.** Color changes of extrudates

| № | *L* | *a* | *b* | Δ*E* |
|---|---|---|---|---|
| 1 | 65.16 ± 0.21 | 6.19 16 ± 0.10 | 29.77 ± 0.20 | 14.55 ± 0.16 |
| 2 | 76.00 ± 0.20 | 5.09 ± 0.12 | 23.91 ± 0.18 | 10.46 ± 0.18 |
| 3 | 71.38 ± 0.18 | 16.91 ± 0.16 | 39.56 ± 0.21 | 9.09 ± 0.20 |
| 4 | 78.94 ± 0.16 | 3.87 ± 0.14 | 23.41 ± 0.24 | 10.65 ± 0.14 |
| 5 | 79.79 ± 0.21 | 4.55 ± 0.08 | 25.79 ± 0.22 | 8.22 ± 0.22 |
| 6 | 66.73 ± 0.20 | 10.60 ± 0.10 | 30.55 ± 0.20 | 11.78 ± 0.12 |
| 7 | 69.03 ± 0.16 | 6.41 ± 0.14 | 23.90 ± 0.26 | 12.78 ± 0.10 |
| 8 | 65.45 ± 0.21 | 8.07 6 ± 0.12 | 25.88 ± 0.20 | 14.22 ± 0.18 |

Lightness (*L*) values range from 65.16 to 79.79, redness (*a*) from 3.87 to 16.91, yellowness (*b*) between 23.41 and 30.55, and total color difference ($\Delta E$) from 8.22 to 14.55, as shown in Table 4.

The extrudates displayed a darker appearance, supported by the significantly lower (*L*) values compared to those of the initial, non-extruded mixtures ($L_0$). This reduction in lightness indicates that the extrusion process affects the surface color of the material, most likely due to thermal, non-enzymatic browning reactions, such as the Maillard reaction [16]. The lowest (*L*) value was observed when all processing parameters were at their minimum levels, whereas the highest was recorded at 3 % watermelon seed flour content, 180 °C matrix temperature and 18 % moisture content.

The derived model for ($\Delta E$) is presented in eqn. 7.

$$\Delta E = 11.4663 + 0.4996X_1 - 0.2479X_3 + 1.582X_1X_2 + 1.287X_1X_3 - 0.3638X_1X_2X_3 \quad (7)$$

where $R^2 = 99.13$ %   $F = 0.16 < F_c = 3.6$.

The individual effects of WSF content ($X_1$), matrix temperature ($X_2$), moisture content ($X_3$), as well as the interactions between factors, on the total color difference (ΔE) are presented in Fig. 5. It is evident that all investigated factors are significant, except for $X_2$ and the interaction between ($X_2$) and ($X_3$). The greatest positive effect among the single factors is exerted by ($X_1$), followed by a negative influence of ($X_3$).

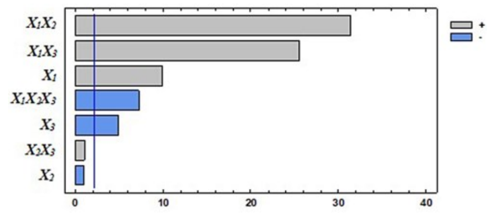


**Fig. 5.** Pareto chart for (Δ*E*)

The combined effect of watermelon seed flour content ($X_1$) and matrix temperature ($X_2$) on the total color difference (Δ*E*) is illustrated in Fig. 6A. It is evident that the highest (Δ*E*) values are obtained at elevated levels of both factors. An increase in WSF content leads to a corresponding rise in (Δ*E*), indicating more pronounced color changes, likely due to intensified Maillard reactions or pigment transformations resulting from thermal and compositional variations.

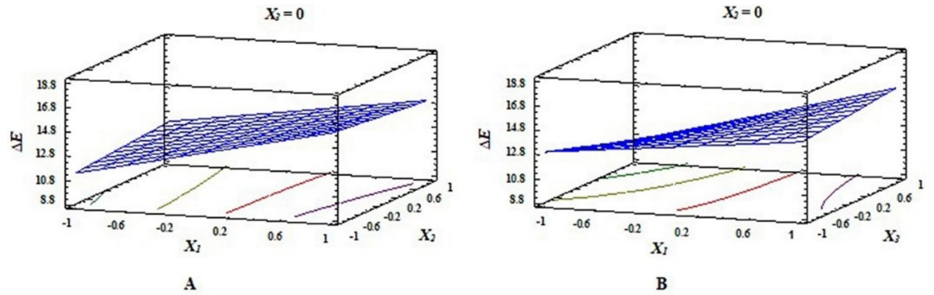


**Fig. 6.** Response surface of Δ$E$, depending on: **A.** watermelon seed flour content ($X_1$) and matrix temperature ($X_2$); **B.** watermelon seed flour content ($X_1$) and moisture content ($X_3$)

To better understand the visual impact of formulation and processing variables, the effect of WSF and moisture content on the total color difference was examined. Figure 6B illustrates the influence of WSF content ($X_1$) and moisture content ($X_3$) on the total color difference (Δ$E$).

The response surface reveals a clear positive correlation between both independent variables and (Δ$E$) values. As the levels of ($X_1$) and ($X_3$) increase, (Δ$E$) also steadily rises, indicating enhanced changes in product color. This combination contributes to more pronounced alterations in visual appearance, likely due to increased pigment diffusion or component interactions during processing. Such changes are critical for ensuring product consistency and consumer acceptance in food formulations.

## CONCLUSION

Appropriate mathematical regression models were developed to investigate the effects of WSF content (3 % and 10 %), matrix temperature (160 °C and 180 °C), and moisture content (14 % and 18 %) on *WAI*, *WSI*, and the color changes of extrudates produced from corn semolina enriched with watermelon seed flour. The *WAI* values ranged from 5.54 g/g to 7.26 g/g, while *WSI* values varied from 11.68 % to 17.03 %. Moisture content exhibited the most pronounced positive effect on *WAI*, whereas watermelon seed flour content had the strongest positive influence on *WSI*. The total color difference (Δ$E$) values ranged from 8.22 to 14.55. Among the single factors, WSF content had the greatest positive impact on (Δ$E$), followed by a negative effect associated with moisture content.

***Acknowledgement:*** *The study was conducted with the kind support of the Science Fund of UFT-Plovdiv, project 10/25-N: Investigation of the extrusion process of cereal raw materials with added watermelon seed flour.*

## REFERENCES

1. I. Boluk, S. Kumcuoglu, S. Tavman, *Foods*, **12**, 1029 (2023).
2. C. M. Galanakis, *Foods*, **10**, 128 (2021).
3. K. Prabha, P. Ghosh, S. Abdullah, R. Joseph, R. Krishman, R. Pradhan, *Future Foods*, **3**, 100019 (2021).
4. M. P. Raja, A. Karthiayani, P. Selvan, V. Nithyalakshmi, *JPHT*, **7**, 56 (2019).
5. M. S. Sanusi, M. O. Sunmonu, S. O. Alasi, A. A. Adebiyi, A. A. Tajudeen, *Appl. Food Res.*, **3**, 100287 (2023).
6. J. A. Japu, S. Ahmed, M. A. Hossain, T. Ahmed, M. S. Ali, *J. Agric.*, **19**, 233 (2021).
7. S. Choton, N. Gupta, J. D. Bandral, N. Anjum, A. Choudary, *PIJ*, **9**, 162 (2020).
8. N. A. Oikonomou, M. K. Krokida, *Int. J. Food Prop.*, **14**, 190 (2011).
9. N. Toshkov, PhD Thesis, UFT, Plovdiv, 2011.
10. N. Toshkov, A. Simitchiev, I. Panchev, V. Nenov, *Sci. work Univ. Food Technol.*, **64**, 270 (2017).
11. N. Toshkov, V. Nenov, B. Bozadjiev, N. Delchev, E. Valov, *Food Sci. Appl. Biotechnol.*, **4**, 177 (2021).
12. AACC International, AACC Approved Methods of Analysis, Method 56-20: Hydration Capacity of Pregelatinized Cereal Products, 9th edn., AACC, St. Paul, MN, (1995).
13. D. Seth, L. S. Badwaik, V. Ganapathy, *J. Food Sci. Technol.*, **52**, 1830 (2015).
14. M. Eftekhariyazdi, M. S. Zenoozian, E. Milani, A. H. Elhami Rad, M. Armin, *Food Sci. Technol. Int.*, **31**, 7 (2024).
15. N. Toshkov, S. Kodinova, B. Bozadjiev, *BIO Web. Conf.*, **102**, 03002 (2024).
16. J. Milan-Carrillo, C. Reyes-Moreno, E. Armienta-Rodelo, A. Carabez-Trejo, R. Mora-Escobedo, *LWT – Food Sci. Technol.*, **33**, 117 (2000).