Effect of carrot pomace addition on the rheological and textural properties of soft wheat pasta dough

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Keywords:

Carrot pomace
Wheat pasta dough
Rheology
Texture
Quality evaluation

Article history:

Received 01.12.2024
Received in revised form 23.03.2025
Accepted 30.06.2025

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DOI: 10.24263/2304-974X-2025-14-2-6

Abstract

Introduction. The trend toward sustainable pasta production includes the incorporation of various unconventional ingredients, such as carrot pomace.

Materials and methods. Common wheat pasta dough supplemented with different carrot pomace varieties – Niagara, Belgrado, Sirkana, and Baltimore (0, 3, 6, 9, and 12%) was evaluated by dynamic rheological methods: frequency sweep, temperature sweep, and creep and recovery test. Dough texture was measured with a texturometer.

Results and discussion. The results revealed significant changes in the rheological and textural properties of soft wheat pasta dough when the amount of added carrot pomace exceeded 6%. A key finding is the consistent increase in dough strength with carrot pomace addition, indicated by notably higher values for both elastic (G′) and viscous (G″) moduli compared to the control. Furthermore, dynamic creep and recovery tests, effectively modeled by the Burgers model, demonstrated a clear reduction in various compliance parameters (J_{max} from $12.64\cdot10^5$ to $1.87\cdot10^5$ Pa^{-1}) as carrot pomace levels in common wheat pasta dough increased from 3 to 12%.

This also indicated dough strengthening and higher resistance to deformation, a conclusion supported by the general increase in steady-state viscosity (from $1.05\cdot10^{-6}$ to $9.25\cdot10^{-6}$ Pa·s).

The thermal properties were also affected, with carrot pomace delaying starch gelatinization, evidenced by higher initial and final gelatinization temperatures. Textural analysis highlighted significant modifications: dough hardness (from 1423.99 to 4579.25g) and gumminess (from 626.16 to 1498.21g) increased, while springiness (from 99.90 to 99.53%), resilience (from 1.04 to 0.88), and cohesiveness (from 0.40 to 0.31) generally decreased as the carrot pomace inclusion was higher.

Conclusions. The potential of carrot pomace as a functional ingredient for modifying dough properties is demonstrated. However, its addition affects the characteristics of pasta dough, indicating the need for further study of pasta quality for recipe optimization.

Introduction

The processing of plant materials generates a large amount of waste rich in valuable substances. Improper disposal of this waste often contributes to environmental pollution. Thus, the valorization of vegetable by-products to reduce the carbon footprint is a current priority aligned with the principles of the circular economy (Stabnikova et al., 2023a). Carrot pomace, a byproduct of juice production, contains a high concentration of bioactive compounds such as pigments and dietary fibers (McKee and Latner, 2000). This makes it a valuable additive for the development of functional foods, including commonly consumed products like pasta.

Semolina, made from durum wheat, which is rich in protein and gluten, is the most commonly used flour in pasta production. However, common wheat flour is also used in pasta production, particularly when durum wheat is less accessible. To enrich common wheat flour with fiber, carrot pomace can be incorporated as a functional ingredient. However, incorporation of fiber-rich ingredients like carrot pomace led to significant changes of dough rheology and texture. These features can predict dough behavior during pasta making, and represent useful tools for further recipe optimizations.

Dietary fiber is increasingly being incorporated into food products such as bread, pasta, and noodles to enhance their nutritional value and offer health benefits (Bashta et al., 2021; Lei et al., 2021; Stabnikova et al., 2023b; Tsykhanovska et al., 2024; Xu et al., 2021). However, the addition of fiber-rich ingredients significantly influences the rheological and textural properties of the dough (Xu et al., 2021). This impact is influenced by factors such as the type, structure, size, and amount of dietary fiber added, as well as its physical properties, including water holding, oil holding, swelling capacity, viscosity, or gel formation (Liu et al., 2019; Sivam et al., 2010).

A key mechanism behind the altered dough properties is the high water-binding capacity of dietary fiber (Bchir et al., 2014; Kultys and Moczkowska-Wyrwisz, 2022). Fiber competes with wheat components, primarily gluten and starch, for the available water during dough mixing. This competition can lead to reduced water availability for gluten hydration and development (Xu et al., 2021), potentially disrupting the gluten network (Asadi et al., 2024), and altering the distribution of moisture among dough constituents (Sivam et al., 2010). Upon hydration, dietary fiber swells and, depending on whether it remains as discrete particles or forms a viscous phase, it can physically disrupt the continuous gluten–starch matrix. The presence of other compounds such as polyphenols and enzymes can also play a role. Polyphenols can interact with gluten proteins through hydrogen bonding or covalent cross-linking, influencing viscoelastic properties (Girard and Awika, 2020; Han et al., 2021). Some fiber sources may contain enzymes (like proteases) that can degrade gluten proteins, weakening the network (Lu et al., 2018). Particle size also influences interaction, affecting hydration rate and gluten development (Liu et al., 2019).

Addition of carrot pomace powder to dough generally leads to increased water absorption, dough development time, and stability (Xu et al., 2021). It can also increase dough consistency and decrease viscosity, but it has been shown to decrease dough extensibility and reduce the mixing tolerance index (Bchir et al., 2014; Xu et al., 2021). Textural analysis of dough enriched with carrot pomace powder indicates decreased cohesiveness and elasticity, while gumminess and chewiness are increased (Asadi et al., 2024). The ratio of soluble to insoluble fiber in carrot pomace influences its effect, with a higher soluble fiber content potentially leading to higher water absorption and swelling (Dhingra et al., 2012; Kultys and Moczkowska-Wyrwisz, 2022). Using carrot puree or paste may yield different results compared to powder, potentially resulting in better quality pasta with lower cooking loss (Wang et al., 2022).

In summary, incorporating carrot pomace and other fiber-rich ingredients into dough formulations significantly alters their rheological and textural properties. These changes are complex and depend on the fiber source, amount, and processing, primarily mediated through water competition, physical interference with the gluten network, and interactions involving other co-present compounds like polyphenols and enzymes. To our knowledge, there are few papers regarding the impact of different carrot pomace varieties on common wheat pasta dough. Thus, the aim of this paper was to investigate the effects of carrot pomace (Niagara, Belgrado, Sirkana, and Baltimore varieties) at different levels (0, 3, 6, 9 and 12%) on common wheat pasta dough rheological and texture properties.

Materials and methods

Materials

This study utilized commercial common wheat flour (*Triticum aestivum*), obtained from Mopan, Suceava, and carrot pomace sourced from a farmer in Bacău, Romania. The carrot pomace came from four distinct varieties: Niagara, Belgrado, Sirkana, and Baltimore.

Common wheat flour was analyzed according to Romanian or International Cereal Chemistry methods, revealing the following characteristics: moisture content by ICC methods 110/1; ash content by ICC 104/1; protein content by ICC 105/2; fiber content by acid and alkaline digestion using a Fibertec 2010 automated analyzer; wet gluten by ICC 106/1. Gluten deformation index of wheat four was determined by SR 90:2007; falling number by ICC 107/1.

Carrot pomace from the four varieties displayed varying chemical characteristics: moisture content was determined by SR EN ISO 665:2020; fat content was measured by SR EN ISO 659:2009; protein levels was analyzed using SR EN ISO 20483:2014; ash content was determined according to SR EN ISO 2171:2023; the fiber content was measured by acid and alkaline digestion using a Fibertec 2010 automated analyzer.

Various wheat dough formulations were investigated. One sample of wheat flour served as a control (without carrot pomace). Other formulations included carrot pomace added to the common wheat flour at different incorporation levels (3%, 6%, 9%, and 12%) for each of the four carrot varieties. Dough was obtained by adding water to the flour mix to achieve 45% moisture and mixing for 15 min. The dough was rested for 15 min before testing.

Rheological measurements

Dynamic rheological properties of the dough were assessed using a Haake dynamic rheometer (MARS 40, Thermo-Haake, Karlsruhe, Germany). This rheometer was equipped with 40 mm parallel plates and a Peltier heating system to maintain a constant temperature. Dough samples were positioned between the plates with a 3 mm gap, and any excess was removed. To prevent moisture loss, the exposed dough surface was coated with a thin layer of vaseline. Before testing, samples rested for 120 s in the measurement position. Measurements were conducted within the dough's linear viscoelastic region, determined by strain sweep tests (0-100 Pa strain, 1 Hz oscillation frequency). Frequency sweep tests were performed at a shear stress of 15 Pa across frequencies from 0.01 to 20 Hz. Temperature sweep tests were run at 4.0 ± 0.1 °C/min, heating from 20 to 100 °C, to identify initial (Ti) and final (Tg) gelatinization temperatures.

Complementing these, creep-recovery tests involved a sudden application of 50 Pa stress for 60 s, followed by a 180 s recovery period to allow the dough to relax. The Burgers model was used for processing the creep and recovery data.

Texture measurements

To assess the pasta dough's texture, 50 g dough spheres were subjected to a double compression down to 50% of their original height. This was performed using a Perten TVT–6700 texturometer (Perten Instruments, Sweden) fitted with a 35 mm cylindrical probe. During the test, a speed of 5.0 mm/s was applied, along with a 20 g trigger force and a 12-second recovery time between compressions. The dough's hardness, springiness, gumminess, and resilience were subsequently recorded.

Statistical analysis

Measurements were performed in at least three replicates. Comparisons of means were conducted via ANOVA, utilizing version 2023 of the XLSTAT program. Principal Component Analysis was performed to evaluate the relationships between the characteristics.

Results and discussion

Characteristics of carrot pomace and wheat flour

Proximate composition of wheat flour and carrot pomace from different carrot varieties was discussed in our previous paper (Luca et al., 2022) an it is shown in Table 1.

Table 1

Proximate composition of wheat flour and carrot pomace from different carrot varieties
(Luca et al., 2022)

Content,%	Pomace from carrot variety				Wheat flour
	Baltimore	Belgrado	Niagara	Sirkana	
Moisture	4.04 ± 0.02^{c}	3.78 ± 0.01^{c}	5.88 ± 0.46^{b}	5.91 ± 0.15^{b}	11.84 ± 0.04^{a}
Protein	6.87 ± 0.06^{e}	8.01 ± 0.06^{d}	8.84 ± 0.12^{c}	9.14 ± 0.06^{b}	10.95 ± 0.00^{a}
Fat	1.00 ± 0.02^{c}	1.01 ± 0.03^{c}	0.70 ± 0.02^{d}	1.13 ± 0.03^{a}	1.06 ± 0.02^{b}
Fiber	12.25 ± 0.29^{c}	13.44 ± 0.73^{b}	14.23 ± 0.19^{b}	15.23 ± 0.76^{a}	0.56 ± 0.04^{d}
Ash	5.29 ± 0.04^{c}	5.89 ± 0.02^{a}	5.56 ± 0.03^{b}	5.89 ± 0.01^{a}	0.46 ± 0.01^{d}

Content of wet gluten in wheat flour was 26.75%. Wheat flour had gluten deformation index 2.50 mm and falling number 354.50 s.

Dough rheological features

The incorporation of carrot pomace affected the rheological properties of the dough (Figure 1). All the samples tested exhibited a solid-like behavior, as suggested by the G′ values greater than G". In general, increasing the level of carrot pomace addition led to higher viscoelastic moduli. Compared to the control, all the samples enriched with carrot pomace presented higher G' and G". Samples containing Belgrado carrot pomace showed lower G′ and G" values compared to the other varieties. Similar to our results, Bigne et al. (2016) obtained higher G' compared to G" for dough with Mesquite flour – a leguminous plant, indicating a prevalence of elastic forces above the viscous ones. Carrot pomace is rich in fibers (Table 1) (Luca et al., 2022) and has significant amounts of polyphenols (Luca et al., 2024). The addition of fiber-rich ingredients to wheat dough determines the increase in water absorption requirements and disrupt the development of the gluten network (Gan et al., 1992).

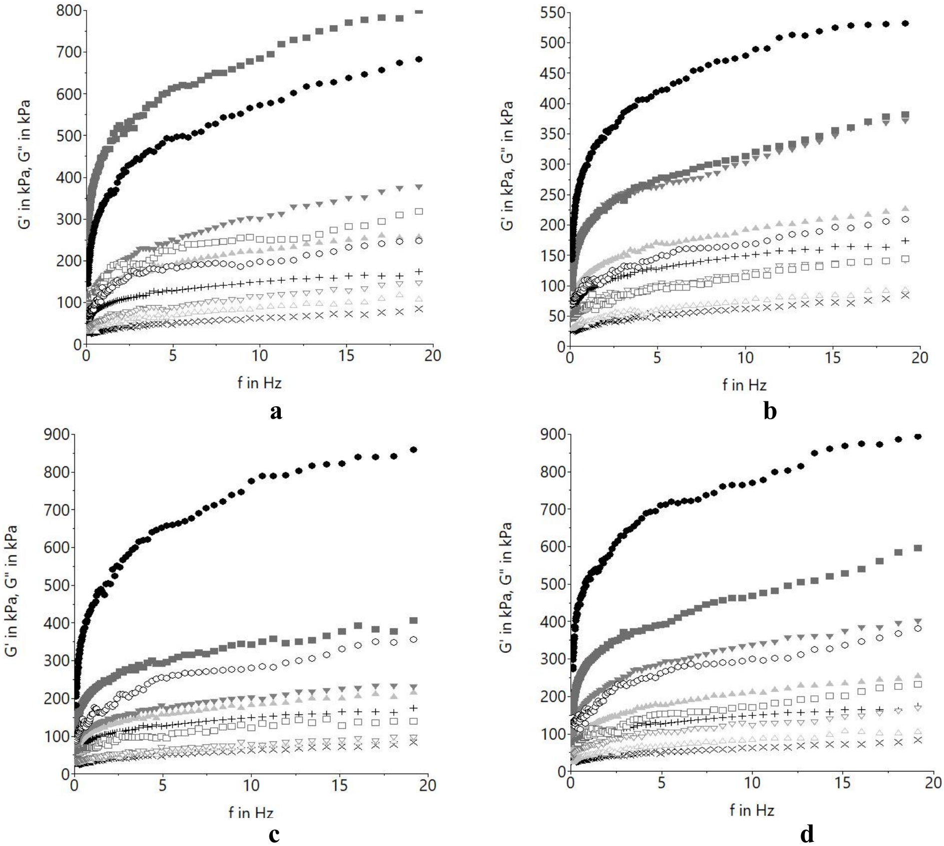

Figure 1. Variation of elastic (G′) and viscous (G") moduli with frequency:
a – Baltimore, b – Belgrado, c – Niagara, d – Sirkana carrot varieties; F2 (0%): + G′, ×G"; 3%: ▲G′, △G"; 6%: ▼G′, ▽G"; 9%: ■G′, □G"; 12%: ●G′, ○G"

These changes in the dough's viscoelastic properties, particularly when enriched with insoluble dietary fibre, can be attributed to modifications in the gluten structure, interactions with starch, and the fiber's water-binding capacity, leading to more plastic than elastic dough matrix (Almoumen et al., 2024). Furthermore, the strengthening of the dough may be attributed to the presence of polyphenols in carrot pomace. Interactions between proteins and phenolic compounds can occur through both covalent and non-covalent bonds, playing a key role in the formation, structure, and development of dough (Ozdal et al., 2013).

Creep and recovery experimental data were successfully fitted to Burgers model (R^2 > 0.97). A reduction of instantaneous elasticity – J_{Co}, J_{Ro} and retarded elastic compliance – J_{Cm}, J_{Rm} in both creep and recovery phases was observed as the addition level of carrot pomace was higher, with some exceptions (Table 2). Maximum creep compliance – J_{max} also decreases, as the amount of carrot pomace was higher, suggesting dough strengthening and higher resistance to deformation. Steady-state viscosity – η_o exhibited a general increasing trend as the level of carrot pomace raised. The recovery compliance – J_r was lower as the amount of carrot pomace was higher. The results are in agreements with those reported previously for wheat dough with tomato pomace (Mironeasa and Codina, 2019).

Table 2

Burgers model parameters for creep and recovery tests

Sample	$J_{Co}\cdot10^5$ (Pa^{-1})	$J_{Cm}\cdot10^5$ (Pa^{-1})	λ_C (s)	$\eta_o\cdot10^{-6}$ ($Pa\cdot s$)	$J_{max}\cdot10^5$ (Pa^{-1})	$J_{Ro}\cdot10^5$ (Pa^{-1})	$J_{Rm}\cdot10^5$ (Pa^{-1})	λ_R (s)	$J_r\cdot10^5$ (Pa^{-1})
F2	1.47 ± 0.09^{abAB}	5.31 ± 0.29^{abAB}	33.71 ± 1.99^{aA}	2.98 ± 0.10^{bcA}	5.67 ± 0.46^{abA}	1.29 ± 0.09^{aAB}	2.84 ± 0.18^{abAB}	50.14 ± 7.23^{aAB}	$4.13\pm0.27a^{bAB}$
F2Ba3	1.06 ± 0.10^{aB}	2.80 ± 0.27^{aB}	25.47 ± 1.20^{aA}	5.29 ± 0.47^{cA}	8.05 ± 0.70^{aA}	1.76 ± 0.12^{aB}	3.44 ± 0.28^{aAB}	45.36 ± 3.42^{aA}	5.20 ± 0.40^{aB}
F2Ba6	0.57 ± 0.04^{abB}	3.91 ± 0.15^{bB}	49.66 ± 1.10^{aA}	5.23 ± 0.99^{bcA}	3.58 ± 0.20^{bA}	1.00 ± 0.05^{aB}	1.38 ± 0.10^{bAB}	50.18 ± 0.40^{abA}	2.38 ± 0.15^{abcB}
F2Ba9	0.55 ± 0.04^{bB}	2.40 ± 0.16^{bcB}	26.98 ± 6.17^{aA}	5.64 ± 0.55^{bA}	2.87 ± 0.16^{bcA}	0.87 ± 0.03^{aB}	1.26 ± 0.05^{bAB}	49.58 ± 0.93^{abA}	2.13 ± 0.08^{bcB}
F2Ba12	0.66 ± 0.02^{bB}	2.23 ± 0.14^{cB}	37.87 ± 2.03^{aA}	5.33 ± 0.31^{aA}	2.60 ± 0.03^{cA}	0.43 ± 0.03^{aB}	1.19 ± 0.07^{bAB}	44.68 ± 1.84^{bA}	1.62 ± 0.10^{cB}
F2Be3	3.01 ± 0.14^{aA}	9.95 ± 0.08^{aA}	33.47 ± 1.62^{aA}	1.05 ± 0.07^{cA}	12.64 ± 0.90^{aA}	1.13 ± 0.09^{aA}	7.07 ± 0.18^{aA}	84.43 ± 1.77^{aA}	8.20 ± 0.27^{aA}
F2Be6	1.95 ± 0.04^{abA}	6.41 ± 0.36^{bA}	33.18 ± 2.04^{aA}	3.05 ± 0.19^{bcA}	7.46 ± 0.52^{bA}	3.54 ± 0.20^{aA}	2.94 ± 0.21^{bA}	35.87 ± 0.90^{abA}	6.47 ± 0.40^{abcA}
F2Be9	0.97 ± 0.04^{bA}	3.58 ± 0.15^{bcA}	34.25 ± 0.24^{aA}	4.06 ± 0.17^{bA}	3.98 ± 0.18^{bcA}	1.89 ± 0.07^{aA}	1.34 ± 0.04^{bA}	38.37 ± 2.02^{abA}	3.23 ± 0.11^{bcA}
F2Be12	0.71 ± 0.05^{bA}	2.03 ± 0.12^{cA}	36.80 ± 0.17^{aA}	6.38 ± 0.21^{aA}	2.88 ± 0.27^{cA}	1.69 ± 0.06^{aA}	0.78 ± 0.03^{bA}	12.39 ± 0.45^{bA}	2.46 ± 0.09^{cA}
F2Ni3	0.89 ± 0.06^{aB}	4.96 ± 0.34^{aB}	43.16 ± 1.15^{aA}	2.62 ± 0.16^{cA}	4.67 ± 0.32^{aA}	1.10 ± 0.02^{aAB}	0.89 ± 0.02^{aB}	31.24 ± 0.56^{aA}	1.99 ± 0.04^{aB}
F2Ni6	1.24 ± 0.11^{abB}	3.64 ± 0.39^{bB}	35.86 ± 0.78^{aA}	3.74 ± 0.22^{bcA}	5.82 ± 0.29^{bA}	1.81 ± 0.17^{aAB}	1.13 ± 0.11^{bB}	23.12 ± 0.75^{abA}	2.94 ± 0.28^{abcB}
F2Ni9	0.60 ± 0.04^{bB}	1.61 ± 0.07^{bcB}	35.46 ± 3.49^{aA}	5.99 ± 0.13^{bA}	2.80 ± 0.10^{bcA}	1.60 ± 0.08^{aAB}	0.66 ± 0.01^{bB}	23.82 ± 2.23^{abA}	2.26 ± 0.09^{bcB}
F2Ni12	0.44 ± 0.04^{bB}	1.38 ± 0.09^{cB}	33.78 ± 0.11^{aA}	9.25 ± 0.86^{aA}	1.94 ± 0.14^{cA}	0.84 ± 0.08^{aAB}	0.64 ± 0.03^{bB}	36.64 ± 5.27^{bA}	1.48 ± 0.11^{cB}
F2Si3	1.99 ± 0.18^{aAB}	7.71 ± 0.65^{aAB}	34.13 ± 1.53^{aA}	1.65 ± 0.11^{cA}	8.55 ± 0.67^{aA}	3.43 ± 0.28^{aAB}	2.58 ± 0.09^{aAB}	42.34 ± 1.47^{aA}	6.01 ± 0.36^{aAB}
F2Si6	0.80 ± 0.07^{abAB}	3.10 ± 0.26^{bAB}	33.87 ± 1.09^{aA}	3.93 ± 0.16^{bcA}	3.52 ± 0.39^{bA}	1.04 ± 0.10^{aAB}	1.81 ± 0.11^{bAB}	54.42 ± 4.92^{abA}	2.86 ± 0.21^{abcAB}
F2Si9	1.05 ± 0.08^{bAB}	3.30 ± 0.13^{bcAB}	41.80 ± 2.26^{aA}	4.03 ± 0.09^{bA}	3.88 ± 0.13^{bcA}	0.93 ± 0.03^{aAB}	1.58 ± 0.12^{bAB}	47.75 ± 3.20^{abA}	2.50 ± 0.14^{bcAB}
F2Si12	0.42 ± 0.04^{bAB}	1.90 ± 0.16^{cAB}	42.04 ± 3.73^{aA}	6.78 ± 0.14^{aA}	1.87 ± 0.02^{cA}	0.93 ± 0.03^{aAB}	0.49 ± 0.02^{bAB}	17.49 ± 1.30^{bA}	1.41 ± 0.04^{cAB}

In the same column, a-c – small letters indicate significant differences ($p < 0.05$) among different addition levels, A-B – uppercase letters indicate significant differences ($p < 0.05$) among different carrot varieties, Ba – Baltimore, Be – Belgrado, Ni – Niagara, Si – Sirkana carrot varieties, F2 – common wheat flour; 3, 6, 9, and 12 – levels of incorporated carrot pomace.

Lower elastic compliance during the recovery phase indicates smaller recoverable energy, suggesting a less extensively cross-linked gluten network in samples with high amounts of carrot pomace (Mironeasa and Codina, 2019). The reduction in instantaneous compliance may result from gluten dilution in the dough matrix, as a portion of the wheat flour is replaced by non-gluten components from the carrot pomace (Atudorei et al., 2023).

The diminished recovery behavior further suggests that the incorporation of carrot pomace may have led to partial disruption of elastic bonds within the gluten network. The observed strengthening effect may be attributed to the hydroxyl groups present in phenolic compounds from carrot pomace (Iuga et al., 2019; Luca et al., 2024). The phenolic compounds can directly interact with proteins through both non-covalent and covalent bonds, altering protein structure and functionality, thereby influencing the overall quality and functional properties of food products (Baxter et al., 1997). Furthermore, interactions between the insoluble dietary fiber in carrot pomace and wheat proteins may also contribute to increased dough stiffness, supporting previous findings (Iuga et al., 2019).

Dough behavior during heating indicated a delay in starch gelatinization. Ti values increased as the addition level was higher, with some exceptions for 12% Baltimore, Belgrado and Niagara carrot pomace (Figure 2). Tg values exhibited slight increase with carrot pomace addition level raise. Carrot pomace variety did not show significant impact on Tg and Ti. The presence of polyphenols in carrot pomace may explain these results since it was demonstrated that there is an interaction between phenolics and gluten, leading to delay in starch gelatinization and staling (Xu et al., 2019). There are two primary interactions mechanisms between starch and gluten during thermal processing (Jekle et al., 2016): (1) competitive hydration, where both components compete for available water as their structures undergo transformation, and (2) the formation of a gluten network that encases starch granules, thereby restricting their water uptake and hindering gelatinization. Additionally, hydrophilic phenolic compounds may compete with starch for water and form non-covalent interactions with starch molecules. These interactions can alter the system's pH, subsequently influencing starch granule hydration, gelatinization behavior, and pasting characteristics (Jekle et al., 2016). Another study observed that incorporating certain phenolics from blackcurrant into wheat flour increases starch gelatinization temperatures (Sivam et al., 2012).

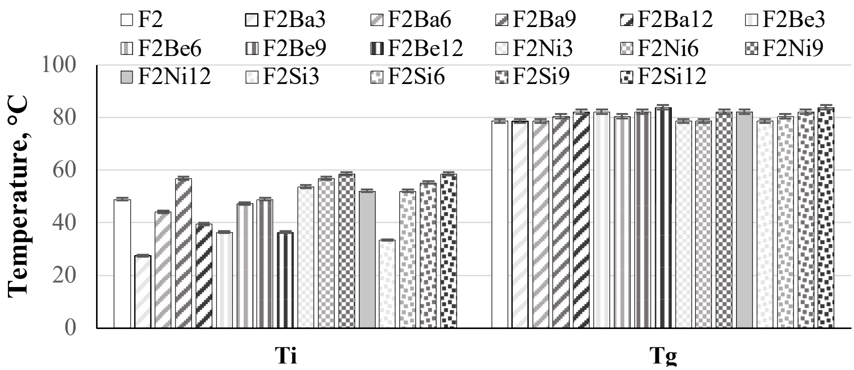

Figure 2. Initial (Ti) and final (Tg) gelatinization temperatures of dough with carrot pomace: Ba – Baltimore, Be – Belgrado, Ni – Niagara, Si – Sirkana carrot varieties, F2 – common wheat flour

Dough texture features

The structure of the gluten network plays a key role in determining dough texture. Incorporation of fiber-rich ingredients like carrot pomace led to significant changes of textural parameters, depending on the addition level (Table 3).

Table 3

Texture features of dough

Sample	Hardness (g)	Springiness (%)	Gumminess (g)	Resilience (adim.)	Cohesiveness (adim.)
F2	1423.99±119.74^{dB}	99.90±0.15^{aA}	657.35±27.08^{cA}	0.91±0.08^{aA}	0.40±0.05^{aA}
F2Ba3	2093.00±83.44^{dA}	99.73±0.18^{aA}	779.05±59.47^{cA}	1.04±0.07^{aA}	0.35±0.02^{abC}
F2Ba6	2863.67±784.31^{cA}	99.61±0.05^{aA}	860.29±79.68^{cA}	0.95±0.04^{aA}	0.32±0.02^{bcC}
F2Ba9	3393.50±286.38^{bA}	99.55±0.21^{aA}	904.20±60.24^{bA}	0.93±0.03^{aA}	0.31±0.02^{bcC}
F2Ba12	3550.00±95.35^{aA}	99.64±0.13^{aA}	1194.02±172.00^{aA}	0.88±0.08^{aA}	0.32±0.01^{cC}
F2Be3	1676.50±75.94^{dAB}	99.80±0.05^{aA}	626.16±53.51^{cA}	0.99±0.03^{aA}	0.39±0.01^{abB}
F2Be6	2221.67±295.17^{cAB}	99.76±0.16^{aA}	639.54±37.79^{cA}	0.98±0.06^{aA}	0.36±0.01^{bcB}
F2Be9	3225.00±219.73^{bAB}	99.72±0.09^{aA}	1085.23±55.51^{bA}	1.01±0.02^{aA}	0.34±0.01^{bcB}
F2Be12	3461.25±350.08^{aAB}	99.66±0.08^{aA}	1100.24±107.77^{aA}	0.97±0.05^{aA}	0.33±0.01^{cB}
F2Ni3	1520.00±75.74^{dAB}	99.71±0.20^{aA}	593.41±70.45^{cA}	0.89±0.03^{aA}	0.36±0.01^{abBC}
F2Ni6	2202.25±50.17^{cAB}	99.73±0.21^{aA}	776.08±74.66^{cA}	1.00±0.07^{aA}	0.33±0.02^{bcBC}
F2Ni9	2395.00±99.98^{bAB}	99.69±0.19^{aA}	848.05±83.60^{bA}	0.95±0.04^{aA}	0.35±0.00^{bcBC}
F2Ni12	4579.25±297.69^{aAB}	99.86±0.05^{aA}	1498.21±134.04^{aA}	1.03±0.07^{aA}	0.32±0.02^{cBC}
F2Si3	1894.00±67.55^{dAB}	99.78±0.24^{aA}	651.89±92.87^{cA}	0.96±0.06^{aA}	0.35±0.02^{abBC}
F2Si6	2281.25±36.68^{cAB}	99.77±0.10^{aA}	847.08±25.7^{cA}	0.97±0.04^{aA}	0.36±0.02^{bcBC}
F2Si9	2748.75±94.75^{bAB}	99.58±0.08^{aA}	951.85±69.95^{bA}	1.01±0.03^{aA}	0.35±0.02^{bcBC}
F2Si12	3500.67±193.71^{aAB}	99.53±0.13^{aA}	1150.39±108.06^{aA}	0.94±0.04^{aA}	0.33±0.01^{cBC}

In the same column, a-d – small letters indicate significant differences ($p < 0.05$) among different addition levels, A-C – uppercase letters indicate significant differences ($p < 0.05$) among different carrot varieties, Ba – Baltimore, Be – Belgrado, Ni – Niagara, Si – Sirkana carrot varieties, F2 – common wheat flour

Dough hardness and gumminess increased with higher levels of carrot pomace, while springiness, resilience, and cohesiveness generally decreased. Carrot pomace level influenced significantly ($p < 0.05$) only cohesiveness. Fibers from carrot pomace could be responsible for hardness increase and reduction of elasticity of pasta dough. For instance, studies have shown that components like water-unextractable solids, found in wheat flour with higher milling extraction rates, could reduce both gluten yield and extensibility, as well as disrupt gluten particle interactions (Wang et al., 2003). Additionally, fiber components may hinder gluten agglomeration (Noort et al., 2010), physically disrupt the gluten matrix, and limit the water available for gluten development (Ktenioudaki et al., 2013; Wang et al., 2003). Dahdah et al. (2024) reported smaller extensibility of dough with freeze-dried olive pomace due to a weaker gluten matrix due to fibre incorporation, leading to stiffer and firmer dough. Glutenin serves as the base of the gluten network and plays a key role in providing elasticity to dough by forming intermolecular disulfide bonds with other glutenin molecules (Dahdah et al., 2024; Shewry et al., 2000). These cross-links result in a stable, elastic structure that contributes to the dough's resistance (Shewry et al., 2000). Therefore, diluting the gluten content with fiber-rich ingredients like carrot pomace leads to a reduction in springiness and dough resilience.

Relationships between variables

Pearson correlations coefficients are presented in Table 4.

Table 4

Pearson correlations between variables

Variables	G'_{10Hz}	G''_{10Hz}	T_i	Hardness	Springiness	Gumminess	Resilience	Cohesiveness	J_{Co}	J_{Cm}	λ_C	η_o	J_{max}	J_{Ro}	J_{Rm}	λ_R	J_r
G'_{10Hz}	**1**																
G''_{10Hz}	**0.99**	**1**															
T_i	0.34	0.36	**1**														
Hardness	**0.89**	**0.87**	0.19	**1**													
Springiness	-0.48	**-0.49**	-0.26	-0.37	**1**												
Gumminess	**0.83**	**0.80**	0.17	**0.95**	-0.23	**1**											
Resilience	-0.04	-0.03	-0.23	0.15	0.24	0.18	**1**										
Cohesiveness	**-0.68**	**-0.66**	-0.15	**-0.79**	**0.65**	**-0.65**	-0.03	**1**									
J_{Co}	**-0.60**	**-0.59**	-0.43	**-0.64**	**0.50**	**-0.64**	0.20	**0.68**	**1**								
J_{Cm}	**-0.64**	**-0.61**	-0.39	**-0.68**	0.44	**-0.71**	0.01	**0.67**	**0.94**	**1**							
λ_C	0.03	0.04	0.26	0.07	-0.37	0.09	-0.36	-0.15	-0.25	-0.05	**1**						
η_o	**0.79**	**0.77**	0.25	**0.85**	-0.29	**0.85**	0.14	**-0.69**	**-0.80**	**-0.87**	0.02	**1**					
J_{max}	**-0.68**	**-0.65**	**-0.57**	**-0.69**	0.47	**-0.70**	0.29	**0.62**	**0.94**	**0.89**	-0.33	**-0.76**	**1**				
J_{Ro}	-0.45	-0.42	-0.31	-0.37	0.32	-0.46	0.26	0.22	**0.50**	0.46	-0.27	-0.42	0.48	**1**			
J_{Rm}	**-0.50**	**-0.49**	**-0.55**	**-0.55**	0.44	**-0.54**	0.26	**0.65**	**0.89**	**0.82**	-0.35	**-0.64**	**0.92**	0.21	**1**		
λ_R	-0.29	-0.29	-0.32	-0.33	0.29	-0.33	0.09	0.44	**0.57**	**0.60**	-0.20	**-0.49**	**0.58**	-0.18	**0.78**	**1**	
J_r	**-0.60**	**-0.58**	**-0.58**	**-0.61**	**0.49**	**-0.64**	0.33	**0.62**	**0.94**	**0.86**	-0.40	**-0.71**	**0.95**	**0.61**	**0.91**	**0.56**	**1**

Ba – Baltimore, Be – Belgrado, Ni – Niagara, Si – Sirkana carrot varieties, F2 – common wheat flour, values with bold are significant at $p < 0.05$.

Strong positive correlation was obtained between G' and G" ($p < 0.05$, r = 0.99), which was in agreement with previous report for grape peels-containing dough (Mironeasa et al., 2019).

G' and G" were positively correlated with hardness, gumminess, η_o ($p < 0.05$, r > 0.79), and negatively with cohesiveness, J_{Co}, J_{Cm}, J_{max}, J_{Rm}, and J_r ($p < 0.05$, r > -0.50). Similar strong positive correlations between G' and G" with hardness and gumminess were obtained by (Ganesan et al., 2023) for cookies with brewer's spent grain by-product. Negative correlations ($p < 0.05$, r > -0.55) were observed between T_i and J_{max}, J_{Rm}, and J_r. Hardness and gumminess were positively correlated with η_o ($p < 0.05$, r > 0.85), and negatively with J_{Co}, J_{Cm}, J_{max}, J_{Rm}, and J_r ($p < 0.05$, r > -0.54). Springiness was positively correlated with cohesiveness, J_{Co} and J_r ($p < 0.05$, r > 0.49). Significant positive correlations (p < 0.05, r > 0.62) were obtained between cohesiveness and J_{Co}, J_{Cm}, J_{max}, J_{Rm}, and J_r, while with η_o the correlation was negative ($p < 0.05$, r = -0.69). J_{Co}, and J_{Cm} were positively correlated with J_{max}, J_{Rm}, λ_R and J_r ($p < 0.05$, r > 0.50), and negatively with η_o ($p < 0.05$, r > -0.80). Negative correlations were observed between η_o and J_{Rm} and λ_R ($p < 0.05$, r > -0.49), while J_{max} was positively correlated with J_{Rm}, λ_R and J_r ($p < 0.05$, r > 0.58). Significant positive correlations were obtained between J_r and J_{max}, J_{Ro}, J_{Rm}, and λ_R ($p < 0.05$, r > 0.61). Previous research regarding wheat flour dough rheological properties revealed significant positive correlations between extensibility and maximum recovery strain (Wang and Sun, 2002).

Principal Component analysis (PCA) revealed the relationships between the rheological and texture parameters of dough (Figure 3).

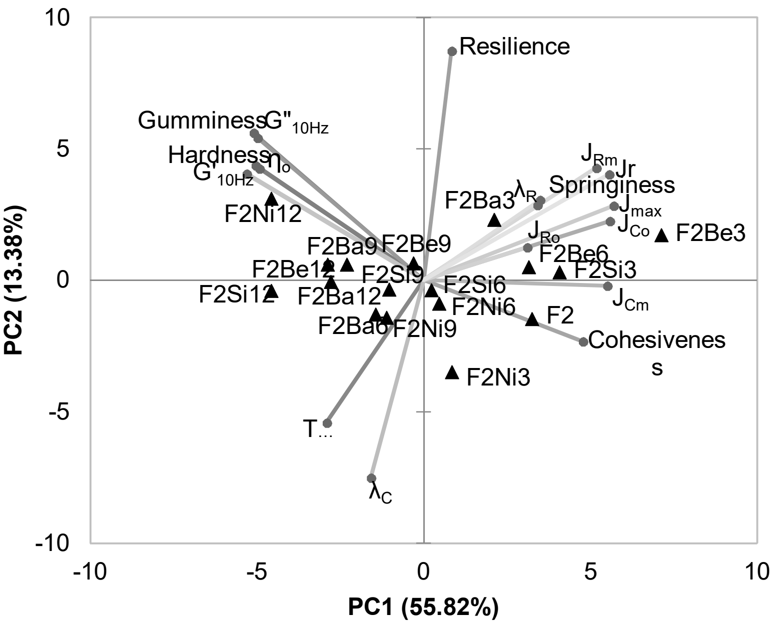

Figure 3. Principal Component Analysis bi-plot:
Ba – Baltimore, Be – Belgrado, Ni – Niagara,
Si – Sirkana carrot varieties, F2 – common wheat flour

A total variance of 69.20% was explained by PC1 (55.82%) and PC2 (13.38%). PC1 was associated with J_{Co}, J_{Cm}, η_o, J_{max}, J_{Ro}, J_{Rm}, λ_R, J_r, springiness, cohesiveness, hardness, gumminess, G' and G", while PC2 was associated with resilience, T_i and λ_C. Almost all the samples with 3 and 6% carrot pomace, along with the control (F2) were positioned in the right part of the graphic, while the samples with higher addition levels (9 and 12%) were located in the left quadrants.

Conclusions

The incorporation of carrot pomace has a significant effect on the rheological and textural properties of the dough. The results demonstrate that increasing carrot pomace levels generally lead to a more solid-like dough behavior, characterized by higher viscoelastic moduli and increased resistance to deformation. Furthermore, the addition of carrot pomace was found to delay starch gelatinization, indicating a modification in the dough's thermal properties. From a texture point of view, the enriched dough exhibited increased hardness and gumminess, while springiness, resilience, and cohesiveness were lower. Correlation analysis reinforced these observations, revealing strong positive relationships between viscoelastic moduli and dough hardness/gumminess, and negative correlations with various creep and recovery parameters. These results underscore the potential of carrot pomace as a functional ingredient for modifying dough properties, although further research is needed to optimize its application for specific product development.

Acknowledgment
Mădălina Ungureanu-Iuga was funded by the Romania National Council for Higher Education Funding, CNFIS, project number CNFIS-FDI-2025-F-0603.

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Cite:

UFJ Style

Luca M.I., Ungureanu-Iuga M., Batariuc A., Mironeasa S. (2025), Effect of carrot pomace addition on rheology and texture of soft wheat pasta dough, *Ukrainian Food Journal*, 14(2), pp. 259–272, https://doi.org/10.24263/2304-974X-2025-14-2-6

APA Style

Luca, M.I., Ungureanu-Iuga, M., Batariuc, A., & Mironeasa, S. (2025). Effect of carrot pomace addition on rheology and texture of soft wheat pasta dough. *Ukrainian Food Journal, 14*(2), 259–272. https://doi.org/10.24263/2304-974X-2025-14-2-6