# EFFECT OF FRUIT POWDER ADDITION ON DOUGH RHEOLOGY AND BAKERY PRODUCT SAFETY - REVIEW
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# *INFLUENȚA ADAOSULUI DE PUDRE DE FRUCTE ASUPRA PROPRIETĂȚILOR REOLOGICE ȘI A SIGURANȚEI PRODUSELOR DE PANIFICAȚIE - REVIEW*

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***Keywords:** fruit powders, wheat flour, dough, rheological properties, functional ingredients, bakery products*

## ABSTRACT
*In the modern food industry, improving bakery product quality through functional ingredients is a growing focus. Fruit powders or flours derived from pulp or by-products such as peels and seeds provide fibers, antioxidants, and bioactive compounds that enhance nutritional value, functionality, and shelf life. However, soil contamination with heavy metals negatively impacts cereal crops, lowering flour quality and food safety. Incorporating fruit powders from chokeberry, sea buckthorn, currants, cranberries, rosehip, raspberry, apple, or grape can mitigate these effects while improving dough properties and texture. This study demonstrates fruit powders' potential as sustainable ingredients for high-value functional bakery products.*

## REZUMAT
*În industria alimentară modernă, îmbunătățirea calității produselor de panificație prin utilizarea ingredientelor funcționale reprezintă un domeniu de interes tot mai mare. Pudrele sau făinurile din fructe obținute din pulpă sau din produse secundare, precum cojile și semințele, oferă fibre, antioxidanți și compuși bioactivi care îmbunătățesc valoarea nutrițională, funcționalitatea și durata de valabilitate. Totuși, contaminarea solului cu metale grele afectează negativ culturile de cereale, reducând calitatea făinii și siguranța alimentară. Incorporarea pudrelor din fructe precum aronia, cătina, coacăzele, merișoarele, măceșele, zmeura, merele sau strugurii poate atenua aceste efecte, îmbunătățind în același timp proprietățile aluatului și textura. Acest studiu demonstrează potențialul pudrelor din fructe ca ingrediente durabile pentru produse de panificație funcționale, cu valoare adăugată ridicată.*

## INTRODUCTION
The bakery industry is one of the most important food production sectors, providing staple products that supply carbohydrates, proteins, dietary fiber, and bioactive compounds essential for human nutrition. In recent years, its role has expanded due to increasing consumer demand for functional foods, health-promoting ingredients, and sustainable production systems *(Galanakis, 2021; Zarzycki et al., 2024)*.

In this context, fruit powders obtained from whole fruits or processing by-products (peels, seeds) have gained particular interest for their fiber, vitamins, polyphenols, and other bioactive compounds *(Salehi, 2020; Krakowska-Sieprawska et al., 2024)*. Unlike extracts or juices, fruit powders offer higher stability, better preservation of bioactive compounds, and easier handling, while also supporting circular economy principles by valorizing by-products *(Krakowska-Sieprawska et al., 2024)*. Meanwhile, wheat flour quality is increasingly affected by climate change, intensive agricultural practices, and environmental pollution, which alter protein, gluten, and starch content, directly impacting dough stability and rheological behavior. The addition of fruit powders represents a promising strategy to counterbalance these effects, as their antioxidants, fibers, and bioactive compounds contribute to maintaining product quality, nutritional value, and shelf life *(Han et al., 2025; Murariu et al., 2025)*.

Fruit powders also provide functional health benefits, including antioxidant and anti-inflammatory activity, cardiovascular protection, glycemic regulation, and support for gut microbiota. Fruits such as chokeberry, cranberry, blueberry, pomegranate, and sea buckthorn have been widely studied, showing improvements in nutritional and sensory profiles through natural color, flavor, and preservation properties *(Meng et al., 2019; Kasprzak-Drozd et al., 2021)*. However, their incorporation modifies dough rheology, affecting development time, elasticity, extensibility, and gas retention, which in turn determines loaf volume, crumb structure, and texture. These changes require technological adjustments to preserve desirable quality *(Fadiji and Pathare, 2023; Cacak-Pietrzak et al., 2023; Kolesárová et al., 2025)*.

Examples such as the addition of chokeberry, sea buckthorn, or rosehip demonstrate both nutritional and functional benefits, as well as technological challenges. For instance, chokeberry, although rich in anthocyanins and fiber, enhances nutritional value and extends shelf life but significantly affects dough rheology *(Fadiji and Pathare, 2023; Cacak-Pietrzak et al., 2023)*. Sea buckthorn, high in vitamins and antioxidants, offers important functional benefits but requires optimization of addition levels to avoid compromising bread texture and flavor *(Bal et al., 2011; Wang et al., 2016; Stanciu et al., 2023)*. Similarly, rosehip seed flour (Rosa Canina L.) can enrich bakery products with fiber, protein, and minerals, but it also alters dough rheology, necessitating formulation and processing adjustments *(Gül and Şen, 2017; Cingöz and Şahin, 2023; Sanfilippo et al., 2025)*. Moreover, currants, due to their high vitamin C and anthocyanin content, have been linked to enhanced antioxidant capacity and color stability in baked goods.

Raspberries and blackberries, rich in bioactive compounds such as fibers and polyphenols, contribute to higher nutritional value while improving natural aroma and color. Grapes and their by-products (pomace) are valuable sources of resveratrol and fiber, successfully applied to increase product stability, functionality, and shelf life *(Kierońska et al., 2024; Mandache et al., 2025; Salehi, 2020)*. From a technological perspective, these challenges have prompted strategies to balance enrichment with processing performance, including optimization of addition levels, the use of functional improvers (vital gluten, enzymes), and adjustments to fermentation conditions *(Lauková et al., 2016; Murariu et al., 2025)*. Considering the increasing demand for functional bakery products and the complexity of dough systems, understanding the mechanisms behind fruit powder-induced rheological modifications remains a research priority. Furthermore, fruit powders may play a dual role, enhancing nutrition while mitigating the negative impact of environmental contaminants on wheat-based products by improving antioxidant content, dough stability, and product safety.

Raspberries and blackberries, rich in bioactive compounds such as fibers and polyphenols, contribute to higher nutritional value while improving natural aroma and color, whereas grapes and their by-products (pomace) are valuable sources of resveratrol and fibers, successfully applied to increase product stability, functional properties, and shelf life *(Kierońska et al., 2024; Mandache et al., 2025; Salehi, 2020)*. From a technological perspective, these challenges have prompted strategies to balance enrichment with processing performance, including optimization of addition levels, the use of functional improvers (vital gluten, enzymes), and adjustments of fermentation conditions *(Lauková et al., 2016; Murariu et al., 2025)*. Considering the increasing demand for functional bakery products and the complexity of dough systems, understanding the mechanisms behind fruit powder-induced rheological modifications remains a research priority. In addition, fruit powders may play a dual role: enhancing nutrition while helping mitigate the negative impact of environmental contaminants on wheat-based products by improving antioxidant content, dough stability, and product safety.

## MATERIALS AND METHODS

This paper is a review based on the analysis of scientific articles, conference papers, books, and relevant online publications. Sources were retrieved from international databases (Scopus, Web of Science, Google Scholar) for the period 1999-2025, with emphasis on the most recent contributions (2020-2025). Keywords used were "fruit powders," "wheat flour," "dough rheology," "functional bakery products," "antioxidants," and "bioactive compounds." Publications focusing on the effect of fruit powders on the rheological, nutritional, and technological properties of wheat flour dough were selected. The information was synthesized and grouped into key categories: gluten hydration, dough development time, elasticity and extensibility, gas retention, viscoelastic properties, and functional benefits.text.

## RESULTS

The literature consistently reports that the addition of fruit powders influences both the rheological behavior of dough and the nutritional and sensory quality of bakery products. The effects depend on fruit type, chemical composition, and incorporation level, being largely driven by the interactions of fibers, polyphenols, anthocyanins, vitamins, and the gluten network in wheat flour. In general, moderate additions (3-8%) improve the functional and nutritional profile of bread, whereas higher concentrations (>10%) often cause undesirable changes in dough volume, texture, and rheological performance *(Djeghim et al., 2021)*.

**Impact of fruit powder addition on dough rheological behavior**

Existing studies show that fruit powders induce significant changes in wheat dough properties, primarily through their content of soluble and insoluble fibers, polyphenols, organic acids, and sugars *(Della Valle et al., 2022)*. Key rheological parameters affected include water absorption, dough development time, elasticity, extensibility, gas retention capacity, and viscoelastic properties, all of which directly influence bread quality.

**Water absorption capacity and gluten hydration**

Dough quality refers to the set of properties that determine its technological performance in the breadmaking and baking process, including softness, extensibility, stretchability, elasticity, stability, and the balance between moisture, stickiness, and dryness *(AbuDujayn et al., 2022)*. These characteristics largely depend on flour composition, especially gluten proteins (glutenin and gliadin), fiber content, hydration, and water absorption capacity, as well as on mixing, fermentation, and baking conditions. High-quality dough must be extensible enough to expand during fermentation/proofing, but also elastic enough to retain the produced gases without tearing or becoming too rigid. Farinographic parameters, such as water absorption, dough development time, dough stability, mixing tolerance index, and degree of softening, are key indicators commonly used for evaluating dough quality. These were determined using a Farinograph Brabender (Duisburg, Germany), according to ISO 5530-1:2013 *(Lauková et al., 2016)*.

The chemical composition of commercial apple powder and fine wheat flour was reported in a previous study by *Lauková et al., (2016)*. The apple powder contained 46.1% total dietary fiber, of which 20.4% was pectin. Gluten hydration and water absorption capacity are decisive for dough functionality and loaf volume. Gluten, formed from gliadin and glutenin, provides the viscoelastic network that stabilizes gas cells. Any ingredient competing for water or altering protein interactions will therefore influence dough development and stability *(Schopf and Scherf, 2021; Almutawah et al., 2007)*. Fruit powders enrich bakery products nutritionally, but their bioactive compounds and fibers inevitably compete with gluten for water, altering hydration dynamics *(Isaak et al., 2019)*. Additions rich in insoluble fibers, such as rosehip powder or grape pomace, tend to reduce water absorption and gluten hydration capacity, leading to a less developed protein network *(Sanfilippo et al., 2025; Šporin et al., 2017)*. By contrast, powders high in soluble fibers (e.g., blackcurrant, raspberry) exert more moderate effects, retaining water in a gel-like form and contributing to a more uniform dough texture *(Alba et al., 2020; Cacak-Pietrzak et al., 2023)*.

Moreover, the high pectin content of certain fruits (citrus, apples) may increase water-holding capacity, though often accompanied by reduced gluten elasticity due to interference with protein bonding *(Sharoba et al., 2013; Mudgil, 2017)*. Other polysaccharides, such as β-glucans and arabinoxylans, redistribute water and destabilize protein structures, resulting in doughs with reduced elasticity and extensibility *(Welc-Stanowska et al., 2023)*. In the study of *Schopf and Scherf (2021)*, ten commercial vital gluten samples were analyzed to determine the factors underlying their variable baking performance. Protein composition (gliadins and glutenins), free thiols, and disulfide bonds were quantified, and micro-baking trials were performed using both a complex bread mix and a weak wheat flour. The authors demonstrated that bread quality was not determined by protein composition, but rather by water absorption capacity, with each sample showing a distinct optimal hydration level for maximum loaf volume. As illustrated in Figure 1, samples hydrated at or near their optimal level produced larger, well-aerated breads, while those under- or over-hydrated yielded smaller, denser loaves.

This highlights that industrial baking performance can only be ensured by adjusting water addition to the hydration properties of each gluten batch, even though this practice is rarely applied.

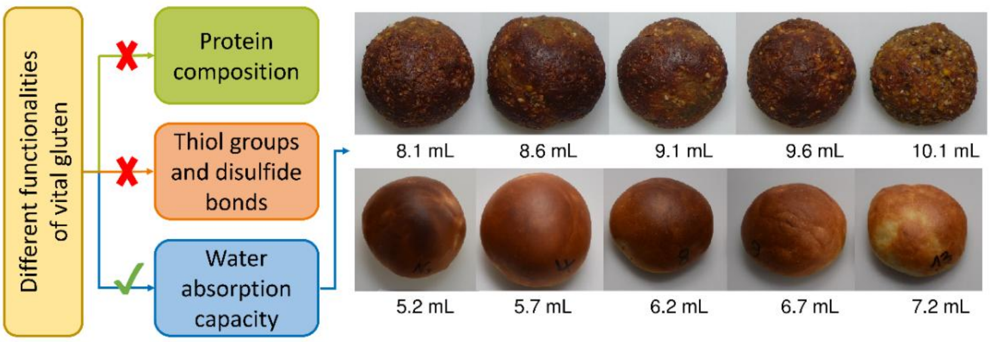


**Fig. 1 - Functional performance of different vital gluten samples in breadmaking. Bread volumes varied as a consequence of differences in water absorption capacity, while protein composition and disulfide bonding were not decisive factors** *(Schopf and Scherf, 2021)*

Therefore, assessing the impact of fruit powders on water absorption and gluten hydration is critical for understanding dough rheology and for adjusting processing conditions to maintain both nutritional and sensory quality. A synthesis of literature findings is presented in Table 1, which summarizes the effects of different fruit powders on water absorption, gluten hydration, and baking outcomes.

**Table 1**

**Effect of fruit powders on water absorption and gluten hydration**

| Fruit powder / additive | Effect on water absorption | Effect on gluten hydration | Consequences for dough / bread quality | References |
|---|---|---|---|---|
| Rosehip, chokeberry | Decrease (due to high insoluble fiber content) | Limit gluten hydration | Increased dough stability but reduced extensibility; lower loaf volume | *Matas et al., 2022; Cacak-Pietrzak et al., 2023* |
| Berries (e.g., blackcurrant, raspberry) | Moderate effect on water absorption | Partial preservation of gluten hydration | Stiffer dough with slower fermentation and reduced loaf volume; pre-hydration mitigates negative effects | *Stanciu et al., 2023; Reißner et al., 2020* |
| Apple powder (hydrated) | Significant increase (e.g., from ~58% to ~75%) | Extended dough development time, reduced mixing tolerance | More stable dough, but less resistant to mechanical stress | *Lauková et al., 2016* |
| Apple pomace (dried) | Increased water absorption | Weakened gluten network at high inclusion levels | Firmer texture of final products, lower loaf volume, impaired crumb quality | *Usman et al., 2020; Jannati et al., 2018* |
| Pomegranate powder | Moderate increase in water absorption | Improved cohesiveness and elasticity | Enhanced dough viscoelasticity and texture at 4-12% addition; high levels may deteriorate structure | *Zhang et al., 2023* |
| Sprouted wheat | Decrease (due to higher enzymatic activity, e.g., amylases and proteases) | Lower gluten index, weaker aggregation | Softer, less viscoelastic dough | *Annor et al., 2015* |
| β-glucans (barley, yeast) | Redistribution of water (effective decrease for gluten) | Formation of a weaker, less elastic protein network | Decreased elasticity, cohesion, and dough stability | *Welc-Stanowska et al., 2023* |
| Fruit/vegetable by-products (fiber-rich) | Moderate increase at low levels; decrease at high levels | Interaction with gluten proteins, limiting hydration | Good dough performance at moderate levels; impaired gluten network at higher doses | *Djeghim et al., 2021* |
| Technological factors (salt, water level) | Decrease (salt reduces water absorption) | Salt strengthens the gluten network but modifies perceived gluten strength | May mask or amplify the effects of fruit powder additions | *Isaak et al., 2019* |
| Spectroscopic studies on gluten hydration | Changes depending on water content | Hydration alters protein conformation | Direct impact on rheological behavior and bread volume | *Almutawah et al., 2007; Schopf and Scherf, 2021* |

Table 1. Synthesis of literature findings on the effects of fruit powders and related factors on dough rheology. The table summarizes how different fruit-derived ingredients influence water absorption and gluten hydration, highlighting their technological consequences for dough handling, bread volume, and crumb quality.

**Dough development time**

The dough development time is defined as the interval required, during kneading, for the dough to reach the maximum consistency corresponding to the optimal development of gluten. It is one of the central parameters analyzed with the farinograph, usually reported together with stability and degree of softening (Figure 2). This parameter reflects the process of hydration and alignment of gluten proteins into a viscoelastic network capable of retaining fermentation gases *(Suprabha Raj et al., 2023)*, being recognized as a reliable indicator of flour performance *(Oyeyinka et al., 2023)*. From a mechanical perspective, dough development progresses through the increase in apparent viscosity under shear and extension, until over-kneading leads to network degradation.

Development time thus marks the transition from the progressive accumulation of rheological properties to an apparent equilibrium state of a fully developed dough *(Zheng et al., 2000)*.

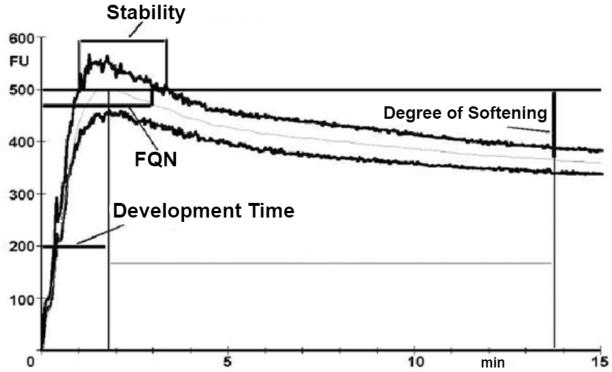


**Fig. 2 - Schematic presentation of Farinograph parameters, Brabender Measurement** *(Mekuria and Emire, 2015)*

The presence of fibers and polyphenolic compounds retards the interactions between glutenins and gliadins, resulting in a less cohesive protein network. Consequently, the development time is often reduced as the level of functional additives increases, with the gluten network reaching maximum stability more quickly but with lower qualitative properties. Recent studies on bread enriched with chokeberry powder and rosehip powder have reported significant decreases in development time, especially with additions above 8-10% *(Cacak-Pietrzak et al., 2023; Chochkov, 2023)*. Similar findings were reported by *Murariu et al. (2025)*, who investigated the effect of integrating wheat flour with blueberry fruits on French-type bread. The study showed that blueberry addition modified gluten development parameters and dough structure, reducing dough stability and mixing tolerance, while also influencing bread volume and texture. At moderate substitution levels, however, the breads were enriched with bioactive compounds, exhibited enhanced antioxidant activity, and achieved favorable sensory scores, demonstrating the potential of antioxidant-rich fruits to improve functional bakery products. As shown in Figure 3, clear differences in appearance and structure were observed between control samples and those supplemented with 5% and 10% fruit powder, according to standardized technological protocols for French-type bread *(ISO 6820-1985; Foods, 2024)*.

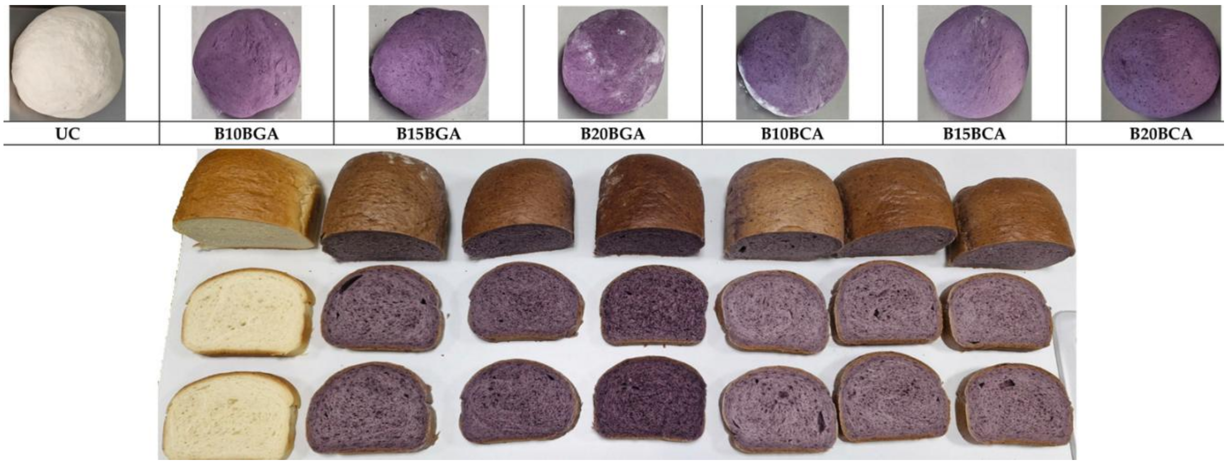


**Fig. 3 - The aspect of the dough and developed bread samples obtained with different fruit powder additions (control, 5%, and 10%)** *(Murariu et al., 2025)*

When comparing instruments, the development time determined with the farinograph strongly correlates with Mixolab parameters, particularly with C1 development and protein weakening at C2. Thus, the profiles obtained for medium- and low-strength flours highlight clear differences in mixing kinetics and protein resistance under the combined action of kneading and controlled temperature *(Koksel et al., 2009)* (Figure 4). Consistent correlations between development time, dough stability, and bread volume have been reported by *Singh et al. (2019)*, while previous studies *(Dabčević et al., 2009; Zhang and Shen, 2021)* confirmed the robustness of the parameter across various types of flours and blends.

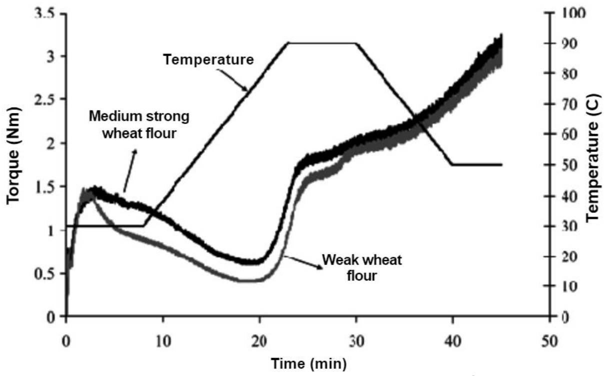


**Fig. 4 - Representative Mixolab curves showing torque development for medium-strong and weak wheat flours under simultaneous mixing and controlled temperature conditions** *(Koksel et al., 2009)*

Agronomic factors such as heat and water stress during wheat grain filling also influence hydration kinetics and, implicitly, development time *(Lama et al., 2022)*. This sensitivity explains the widespread use of the parameter both in wheat breeding and in flour quality control and technological process adjustments (water level, kneading time, and energy). In addition, numerous studies have highlighted the influence of composition on development time: fiber additions interfere with gluten network formation and significantly modify kneading kinetics *(Rosell et al., 2010)*, while changes in salt concentration have shown direct effects on gluten hydration and strength *(Kim et al., 2023)*. More recently, *Mahmoud et al. (2025)* showed that fiber-rich by-products, such as flour obtained from oat drink residue, significantly extend development time, with correlations confirmed through multivariate analyses.

***Elasticity and extensibility***

Dough elasticity and extensibility are strongly modulated by the interactions between dietary fibers and gluten proteins. In general, additions of aronia and rosehip powders increase resistance to extension and stability, but reduce extensibility, leading to stiffer doughs that are more difficult to process. This effect stems largely from polyphenol, protein interactions, which restrict the formation of flexible disulfide bonds. In contrast, softer-fleshed fruits such as raspberries and blackberries, though also polyphenol-rich, exert a less pronounced impact on extensibility due to their relatively lower insoluble fiber content *(Schefer et al., 2021)*.

Elasticity and extensibility together determine a dough's capacity to deform during processing while recovering sufficiently to maintain structural integrity, with direct consequences for sheetability, gas-cell stabilization, and final product quality. As highlighted by *Patel and Chakrabarti-Bell (2013)*, sheetability can be viewed as a practical expression of elasticity: excessive elastic recoil impedes smooth passage through rollers, whereas adequate extensibility permits thinning without rupture. Consequently, flour quality assessments often prioritize extensibility metrics over elasticity itself. Classic cereal chemistry studies have similarly shown that high resistance to extension coupled with insufficient extensibility penalizes loaf volume and processing performance *(Anderssen et al., 2004)*.

Formulation factors further modulate the elastic-viscous balance. *Catherine et al. (2012)* demonstrated that emulsifiers, hydrocolloids, and enzymes can be used to fine-tune extensibility, thereby improving both handling and volume outcomes. Chemometric analyses also support that the relative amounts and quality of gluten fractions, particularly the gliadin-to-glutenin ratio, are strong predictors of extensibility and resistance, linking molecular composition with macroscopic deformation behavior.

Empirical indices derived from instruments such as the alveograph reinforce these findings: the P/L ratio and deformation energy consistently correlate with breadmaking performance. When elasticity dominates at the expense of extensibility, doughs become harder to sheet and more prone to rupture. Conversely, balanced elasticity combined with sufficient extensibility yields smoother dough flow during processing and improved loaf quality *(Gómez et al., 2003)*.

In addition to these aspects, the incorporation of fruit and vegetable powders can significantly affect elasticity and extensibility. In the article Recent applications of powdered fruits and vegetables as novel ingredients in biscuits: a review, *Salehi (2020)* analyzed the use of dried fruit and vegetable powders such as mango, apple, carrot, pumpkin, guava, pomegranate, blueberry, or grape as innovative ingredients in biscuit production. The author showed that such additions can markedly improve the nutritional value of products through fiber, vitamins, minerals, and antioxidant compounds, while at the same time influencing rheological, physicochemical, and sensory properties. The most notable changes occur in dough color, texture, and stability, effects primarily attributed to the fiber and polyphenol content of the powders. The conclusions emphasize that moderate incorporation of these ingredients can provide a balance between nutritional enrichment and the maintenance of acceptable sensory characteristics for consumers.

***Gas retention and bread volume***

Gas retention capacity represents one of the most critical determinants of bread quality, being directly associated with loaf volume, crumb porosity, and overall texture. This parameter reflects the ability of the gluten, starch viscoelastic matrix to capture and stabilize carbon dioxide generated during yeast fermentation and retained throughout proofing and baking *(Dobraszczyk and Morgenstern, 2003)*. A weakened network results in the collapse of gas bubbles, ultimately reducing bread volume.

Fruit powder incorporation into wheat-based formulations markedly influences this parameter. At high substitution levels (>5-10%), almost all fruit powders lead to reduced bread volume *(Bravo, 1999; Tong et al., 2010).* This decline arises primarily from the dilution of gluten proteins and the competition for water by insoluble dietary fibers, which hinder gluten hydration and continuity. As highlighted by *Vitrac et al., (2007)*, such fibers produce thinner gas-cell walls, thereby lowering the gas-holding capacity. Similar effects have been observed with berry pomace, where impaired fermentation and reduced loaf volume were reported unless the pomace was pre-hydrated to release water back into the system *(Reißner et al., 2020).*

Beyond the mechanical effects of gluten dilution and water competition, polyphenols and organic acids present in fruits interact with gluten proteins and starch granules, destabilizing the thin films surrounding $CO_2$ bubbles and weakening interfacial properties *(Lauková, 2016).* Non-starch polysaccharides, such as arabinoxylans, also interfere with gluten crosslinking, yielding fragile bubble walls *(Goesaert et al., 2005).* Likewise, β-glucans can increase dough viscosity but compromise bubble stabilization, leading to reduced volume *(Mastromatteo et al., 2011).*

Nevertheless, moderate additions (3-5%) of fruit powders can preserve loaf volume while enriching the product with bioactive compounds and dietary fibers *(Djeghim et al., 2021).* At these levels, sensory attributes such as color, aroma, and antioxidant capacity are enhanced without dramatic technological drawbacks. Examples include apple or berry pomace, which provide functional enrichment while maintaining acceptable structural quality.

Importantly, the adverse effects of fruit powders on gas retention can be mitigated through technological adjustments. Pre-hydration of pomace reduces direct competition for water, while the use of vital gluten, oxidizing agents (e.g., ascorbic acid, glucose oxidase), or polysaccharide-degrading enzymes (xylanases, cellulases) strengthens the gluten matrix and limits fiber, induced disruption. Process modifications, such as adjusting fermentation time, hydration levels, or mixing energy-can also help restore the rheological properties necessary for efficient gas entrapment *(Al-Marazeeq et al., 2024)*.

***General viscoelastic properties***

The incorporation of fruit powders consistently modifies the viscoelastic profile of wheat doughs, with a common observation being dough stiffening, reflected by increased values of the storage modulus (G′) and loss modulus (G″), which describe the elastic and viscous components of the system, respectively. A higher G′ indicates a more rigid, solid-like behavior, while an increase in G″ reflects stronger energy dissipation during deformation. These shifts are primarily attributed to dietary fibers and non-starch polysaccharides, which absorb water, compete with gluten proteins for hydration, and disrupt the continuity of the protein-starch network *(Meng et al., 2020; Reißner et al., 2020)*.

As a result, dough extensibility and elasticity are generally reduced, limiting the gluten network's capacity to expand and retain gas during fermentation. Studies on berry pomace and apple powders confirm that G′ and G″ values increase in small-amplitude oscillatory tests, indicating more rigid and less deformable doughs *(Lauková et al., 2016; Usman et al., 2020)*. Similar effects have been reported for arabinoxylan- and β-glucan-rich powders, where polysaccharide, protein interactions generate fragile, discontinuous networks with diminished viscoelastic recovery *(Liburdi et al., 2023; Welc-Stanowska et al., 2023)*. At the macroscopic scale, these rheological changes translate into smaller bread volumes, denser crumb structures, and altered texture. Nevertheless, moderate additions can improve technological and nutritional attributes such as water retention, fiber enrichment, and antioxidant capacity without severely impairing dough functionality *(Zhang et al., 2023; Djeghim et al., 2021)*.

From a technological standpoint, bakers often need to compensate for the stiffening effect by adjusting hydration levels, adding functional improvers such as xylanases, cellulases, proteases, or vital gluten, or by optimizing fermentation time, mixing energy, and formulation blends. Thus, fruit powders act as a double-edged ingredient: while enriching breads with fibers, polyphenols, and bioactive compounds, they simultaneously shift dough rheology toward a stiffer, more solid-like state. Monitoring viscoelastic parameters such as G′, G″, and tan δ (G″/G′) provides valuable insight into the balance between elasticity and viscosity, supporting formulation strategies that reconcile nutritional enhancement with desirable technological and sensory qualities *(Dobraszczyk* and *Morgenstern, 2003; Goesaert et al., 2005; Mastromatteo et al., 2011; Zykwinska et al., 2005)*.

These rheological modifications are closely related to the nutritional and technological impacts described in recent research on fruit and vegetable powders. *Salehi (2019)* reviewed the incorporation of mango, apple, carrot, pumpkin, guava, pomegranate, blueberry, and grape powders in biscuits, highlighting their ability to enrich products with fibers, vitamins, minerals, and antioxidants, while simultaneously modifying dough stability, texture, and color due to the presence of fibers and polyphenols. Similarly, *Zahid et al. (2022)* demonstrated that mango peel powder (MPP) and banana peel powder (BPP) significantly increased total phenolic content and probiotic viability in fortified yogurts but altered sensory parameters such as color, decreasing lightness (L*) from 88.42 in control samples to 59.07 with BPP.

The study of *Moraes Crizel et al., (2016)* further supports the technological relevance of fruit byproduct powders, reporting that olive powder exhibited the highest fiber content (≈53.68%), papaya powder had favorable water-holding capacity (≈8.93 g/g) and solubility (≈59.91%), while blueberry powder contained exceptionally high anthocyanin levels (≈2063.4 mg/100 g). These findings underline both the functional potential and the strong influence of bioactive compounds and fibers on dough viscoelasticity. *Ramírez-Pulido et al., (2021)* emphasized the use of fruit processing residues (peels, seeds, pulp) converted into powders rich in dietary fibers, polyphenols, and carotenoids, noting their capacity to improve antioxidant activity but also to alter sensory and functional attributes such as texture, color, and water retention capacity. More recent contributions reaffirm these trends. *Kurćubić et al. (2025)* highlighted that fruit and vegetable powders act as functional food supplements, improving antioxidant content and nutritional value, but affecting sensory acceptance depending on concentration and formulation. *Jiang (2013)* also observed that fruit and vegetable powders can extend shelf life and retain nutritional quality, aroma, and color, but processing and storage conditions are critical for maintaining bioactive integrity.

Together, these findings corroborate that the viscoelastic modifications observed at the rheological level, dough stiffening, increased G′ and G″, reduced extensibility, are manifestations of the high dietary fiber and polyphenol contents in fruit powders. They act both as enhancers of nutritional and antioxidant properties and as disruptors of gluten hydration and network formation, confirming their role as multifunctional yet technologically challenging ingredients.

***Nutritional and functional benefits of fruit powders***

Fruit powders are increasingly recognized as multifunctional ingredients that combine nutritional enrichment with technological functionality in food systems. As highlighted by *Kaur and Kapoor (2001)*, fruits are valuable sources of bioactive compounds, particularly phenolics, vitamins, and minerals, that underpin their antioxidant capacity and health-promoting effects. Converting fruits into powders preserves these compounds while extending shelf life, improving handling, and facilitating incorporation into cereal-based products. In addition, fruit and vegetable powders valorize by-products, reduce food waste, and supply fibers, phytochemicals, and natural pigments, thereby contributing to sustainable food chains *(Galanakis et al., 2020)*.

A major nutritional advantage of fruit powders lies in their high content of polyphenols and flavonoids, compounds widely documented for their antioxidant, anti-inflammatory, and antidiabetic activities. For instance, *Kunyanga et al. (2012)* reported that indigenous fruit powders markedly increase radical-scavenging activity, while *Zhangping Liao et al., (2017)* emphasized their role in glycemic regulation and oxidative stress reduction. Powders derived from tropical fruits such as durian also provide bioactive compounds associated with immune support, cardiovascular health, and improved digestion *(ChenLang Bio, 2023)*. Beyond their nutritional profile, fruit powders deliver functional attributes relevant to food formulation. Drying methods, including spray-drying and freeze-drying, influence the retention of antioxidants and fibers, as well as solubility and powder stability *(Carrasco-Castilla et al., 2012)*. According to *Sagar and Kumar (2010)*, fruit powders act as natural stabilizers, color enhancers, and flavoring agents, thereby improving both technological and sensory performance. Their prebiotic potential has also been highlighted, with studies showing that fermentable fibers and oligosaccharides present in fruit powders stimulate beneficial gut microbiota *(Fan and Roos, 2019)*.

From a functional food perspective, incorporating fruit powders into breads, snacks, and beverages enhances nutritional density by increasing levels of dietary fiber, vitamins C and E, carotenoids, and phenolic acids.

At the same time, they raise consumer appeal through attractive color, flavor, and aroma *(Giri and Mangaraj, 2012; Rivero-Pino et al., 2023)*. Furthermore, *Savaş and Demir, (2025)* demonstrated that fruit powders can act as natural alternatives to synthetic additives by contributing to oxidative stability, microbial safety, and textural improvements.

Overall, the scientific literature consistently demonstrates that fruit powders represent an efficient tool for the development of functional products. They meet consumer demand for healthy, sustainable, and sensorially attractive foods. Successful application, however, depends on the careful choice of fruit source, processing technology, and incorporation level, in order to preserve bioactive compounds while maintaining desirable rheological and technological properties.

Beyond nutritional enrichment, fruit powders may also play a compensatory role in dough systems affected by environmental stressors. Studies have shown that heavy metal contamination and environmental pollutants can impair protein functionality and gluten quality, reducing dough stability. The addition of fruit powders, through their antioxidants and fibers, may help counteract these negative effects, supporting gluten hydration, improving rheological behavior, and maintaining product safety.

Table 2 provides a comparative summary of the main studies on fruit powder supplementation in breadmaking, highlighting the typical levels of addition, their impact on bread volume, and the main rheological effects observed. This synthesis complements the narrative review by allowing a quick comparison across fruit types.

**Table 2**

**Comparative effects of fruit powders on bread dough and bread quality**

| Fruit / By-product | Percentage used (%) | Effect on bread volume | Main rheological effects |
|---|---|---|---|
| Apple (powder / pomace) | 5-15 | Moderate decrease (>10%) at higher levels | Increases water absorption, decreases gluten elasticity |
| Sea buckthorn | 2-10 | Slight decrease, but improves nutritional value | Reduces dough development time, increases dough firmness |
| Aronia (black chokeberry) | 2-8 | Significant decrease (>15%) | Decreases extensibility, increases dough tenacity |
| Rosehip | 3-10 | Moderate decrease, but acceptable sensorially | Reduces dough stability, increases viscosity |
| Blackcurrant | 2-6 | Small decrease, tolerable | Improves gas retention, slightly decreases elasticity |
| Mixed berry fruits (lyophilized) | 2-5 | Slight decrease, compensated by enzyme addition | Reduces farinograph stability, increases dough hydration |
| Prune powder | 5-10 | Moderate decrease, still accepted by consumers | Reduces dough elasticity, increases viscosity |

***The role of environmental factors and contaminants on the quality of flour and dough***

Flour and dough quality are shaped not only by intrinsic compositional and genetic factors, but also by environmental influences and potential contaminants encountered during cultivation, processing, and storage.

From an environmental perspective, the study by *Mikhaylenko et al. (2000)* demonstrated that wheat growing conditions have a decisive effect on flour composition, dough rheology, and baking quality. In Washington State, wheat cultivated in Lind (semi-arid) exhibited higher protein content, superior micro-SDS sedimentation values, and higher water absorption compared with Fairfield (high-rainfall). These differences translated into greater bread volumes for hard wheat grown in Lind, but larger biscuit diameters for soft wheat from Fairfield. Similarly, *Peña (2002)* highlighted the interaction between genetic background and environment, showing that breeding programs may enhance gluten quality and protein composition, but climatic and soil factors can significantly offset or modify these gains, underscoring the need for testing under diverse conditions.

Expanding this view, *Filip et al. (2023)* provided a comprehensive overview of the factors that determine the functional quality of common wheat (*Triticum aestivum L.*). Their review emphasizes that the interplay between genetic factors (protein fractions, gluten composition, enzymatic activity), environmental stresses (temperature, water availability, soil quality), and processing conditions collectively shape dough rheology and baking performance. The authors underline that even small variations in asparagine content, starch properties, or gluten protein distribution can significantly influence technological outcomes such as loaf volume, dough stability, and extensibility, reinforcing the importance of integrated genetic-environmental assessments.

Beyond agronomic conditions, environmental and technological factors can also introduce contaminants. *Maher et al. (2022)* investigated chemical contaminants in bread, identifying acrylamide, furans, polycyclic aromatic amines, 3-monochloropropanediol esters (3-MCPDE), glycidyl esters, as well as natural contaminants such as mycotoxins, heavy metals, and pesticide residues. Acrylamide levels were reported to range from tens to hundreds of µg/kg, with crust containing up to ~80 µg/kg when baked at 270 °C for 15 minutes. Similarly, 3-MCPDE concentrations of ~120 µg/kg and mycotoxin levels exceeding permissible limits were observed, stressing the importance of rigorous monitoring of raw materials and processing conditions. Complementing this, *Varzakas (2016)* emphasized that acrylamide formation, mycotoxin contamination, and other safety risks in wheat products require the integration of advanced analytical methods (e.g., near-infrared spectroscopy) alongside strict quality controls across the processing chain. In line with this, the study *"The role of flours and leavening systems on the formation of acrylamide in the technological process of baked products: Case studies of bread and biscuits"* by *Marianelli et al. (2025)* investigated how flour type and leavening systems influence acrylamide formation in bread and biscuits. Their aim was to identify natural mitigation strategies without compromising product quality. They examined different wheat flours and leavening systems (e.g., yeast vs. alternative agents) in combination with technological parameters such as baking temperature and time, as well as the levels of reducing sugars and asparagine, the main Maillard reaction precursors leading to acrylamide. The study showed that flour selection, combined with leavening system choice and adjustments in baking conditions, can significantly reduce acrylamide formation in bakery products. Their findings suggest that low-asparagine flours and leavening systems that limit the accumulation of reducing sugars before baking are promising strategies for controlling acrylamide levels.

Microbiological and fungal contamination further complicates flour and dough safety. *Sami et al. (2020)* reported microbial loads from 240 samples (flour, dough, bread) collected in Isfahan, Iran. Total bacterial counts ranged from 2.83 ± 0.99 to 6.43 ± 1.12 log CFU/g, while molds varied between 0.00 ± 0.00 and 1.63 ± 0.63 log CFU/g. Bulk breads exhibited higher bacterial counts, whereas flat breads were more susceptible to molds, with species including *Penicillium* (24.4%), *Cladosporium* (20.1%), *Mucor* (20.1%), *Aspergillus* (19.0%), and *Alternaria* (3.8%).

Although levels remained below Iranian legal limits, the high consumption of bread highlights the need for continuous microbial surveillance.

In addition to chemical and microbial hazards, bakery products are vulnerable to physical contaminants. *Mutlu (2025)* reviewed the occurrence of foreign objects such as glass, metal, and plastic fragments, as well as insect and pest residues, arising during packaging, storage, and handling. The study underlined the necessity of preventive measures including visual inspections, storage monitoring, supply chain verification, and good manufacturing practices to safeguard consumer health.

Altogether, these studies converge on the notion that wheat flour and dough quality cannot be evaluated solely through compositional and rheological parameters. Environmental factors shape protein content, gluten functionality, and end-product performance *(Mikhaylenko et al., 2000; Peña, 2002; Filip et al., 2023)*, while chemical, microbial, and physical contaminants *(Maher et al., 2022; Sami et al., 2020; Mutlu, 2025; Varzakas, 2016; Marianelli et al., 2025)* pose safety and technological challenges. Effective management therefore requires an integrated approach, breeding for resilience, cultivating under optimal agro-ecological conditions, applying strict processing controls, and implementing advanced monitoring technologies. Such strategies enable the simultaneous pursuit of high-quality and safe wheat-based products.

## CONCLUSIONS

The integration of fruit powders into wheat flour dough represents a promising strategy for the development of functional bakery products with enhanced nutritional and technological properties. Scientific evidence shows that moderate additions (3-8%) of fruit powders improve fiber, antioxidant, and bioactive content, while maintaining acceptable dough rheology and bread quality. However, higher levels (>10%) often compromise gluten hydration, extensibility, and gas retention, leading to reduced loaf volume and altered texture.

The variability of effects depends strongly on fruit type, composition, and processing conditions, which highlights the need for optimized formulations and the use of technological improvers (enzymes, vital gluten, pre-hydration techniques). From a sustainability perspective, fruit powders valorize processing by-products, reduce waste, and provide natural alternatives to synthetic additives, while also contributing to food security in the context of environmental stressors and soil contamination.

Future research should focus on refining processing strategies, identifying optimal incorporation levels, and exploring consumer acceptance, to fully exploit the potential of fruit powders in next-generation bakery products.

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