

Article

Regularities of the Structure Formation Process in Complex Food Systems During Mixing

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Abstract

An integrated information–energy framework is proposed for assessing boundary kinematic interactions and viscoelastic structure formation during wheat dough mixing in a novel polyhedral chamber. The approach couples spatial boundary velocity fields with non-equilibrium viscous energy dissipation evaluated via thixotropic hysteresis loops. Experimental viscometric measurements conducted at $T = 28\text{ }^{\circ}\text{C}$ demonstrated that progressive structural homogenization reduces specific power input from $5143.7 \rightarrow 4510.2\text{ W/m}^3$, representing a 12.3% energy reduction under investigated operating regimes. Evaluation of thixotropic energy dissipation established an optimal gluten network structuralization time at $\tau = 3.6\text{ min}$, which shortens the mixing cycle by 14% compared to conventional processing without inducing overmixing degradation. A generalized Maxwell constitutive model with a distributed relaxation spectrum was calibrated against experimental flow curves, demonstrating high predictive accuracy ($R^2 > 0.92$, agreement exceeding 90%). The proposed framework establishes a quantitative bridge between boundary shear kinematics, macromolecular gluten preservation, and processing energy efficiency, providing a physically sound foundation for designing high-performance mixing equipment.

Keywords: mixing; rheology; energy efficiency; hydrodynamics; food systems; structure formation



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1. Introduction

Engineering analysis of dough mixing processes requires understanding the coupled hydrodynamic, rheological, and structural behavior of multicomponent food systems subjected to mechanical deformation. During processing, momentum transfer, mass transport,

structural transformations, and physicochemical interactions occur simultaneously, resulting in highly nonlinear behavior of the material. Optimal dough development requires precise control over mechanical energy input to promote gluten network formation without inducing mechanical degradation [1–3].

The hydrodynamic response of food materials is further complicated by spatial variations in density, viscosity, phase distribution, and local flow velocity, all of which depend on operating conditions and equipment design [4,5]. These factors determine not only mixing efficiency but also the formation of the internal viscoelastic structure. Standard industrial mixers often suffer from non-uniform shear stress distribution and excessive thermal dissipation, leading to energy losses and potential over-kneading [2,6]. Therefore, optimization of mixing processes requires an integrated consideration of hydrodynamic and rheological phenomena.

Recent advances in computational mechanics and numerical simulation have considerably expanded the possibilities for analyzing food-processing operations [5,7]. Mathematical modeling, computational fluid dynamics (CFD), and nonlinear rheological analysis are now widely applied for investigating multiphase food systems. Significant progress has been achieved in multi-phase transport modeling [1,4], gluten rheological evolution [2,7–9], discrete particle interactions [10], and mixing kinetics in structured media [6].

From a physical and mechanical perspective, wheat flour dough represents a complex viscoelastic system where mechanical deformation drives protein alignment and network building [2,11]. To adequately capture these interactions, continuum mechanics models must be coupled with parameters reflecting microstructural evolution during mixing [8,11].

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In accordance with the law of conservation of energy, mechanical energy supplied by the mixer is distributed among elastic strain energy, viscous dissipation, and structural rearrangement [3,6]. Quantitative analysis of these energy transformations enables the determination of specific energy consumption associated with nonlinear rheological behavior [3,10]. Minimizing non-productive viscous dissipation represents a critical factor in achieving higher energy efficiency [2,12]. Recent developments in continuous kneading systems featuring texturized geometries by Stadnyk et al. [13] have demonstrated promising results in enhancing energy efficiency and achieving dough homogeneity through such energy-balanced approaches. Similarly, existing numerical models frequently simplify the working boundaries, neglecting the hydrodynamic influence of texturized active surfaces [4,5]. Consequently, a unified constitutive framework integrating geometric features, rheological dynamics, and specific energy partition requires further development.

This study aims to investigate the physical regularities of dough structuralization and energy distribution in a novel laboratory-scale mixer equipped with a texturized cylindrical drum operating within a polyhedral chamber [5,6]. Based on engineering calculations and numerical modeling, this work establishes a mathematical energy-balance framework that quantitatively links mixing dynamics, shear dissipation, and gluten network development [2,3].

2. Materials and Methods

2.1. Raw Materials, Recipe, and General Process Flow

Experimental and theoretical studies were conducted in the research laboratories of the Department of Food Technology Equipment at the Ivan Pulyuy Ternopil National Technical University. The dough was prepared according to the standardized recipe for molded wheat bread (FK) using wheat flour with a moisture content of $13.9 \pm 0.2\%$, a raw gluten content of 24%, and an extensibility of 14 cm [12]. Pressed yeast was utilized as the fermenting agent. Sampling, preparation, and quality assessment of the flour, semi-finished products, and final dough were carried out in strict accordance with standard laboratory testing procedures [12,13]. The physical strength of the dough was evaluated by measuring the spreading of a standard dough ball using an HF testing device [14].

The experiments were performed under isothermal mixing conditions, systematically accounting for the structural, design, and kinematic parameters of both the working body and the mixing chamber [15]. Aligned with global sustainable development goals, this methodology focuses on optimizing the spatial distribution of mechanical energy to minimize the cumulative carbon footprint of the technological process [16]. The dynamic interaction between the mechanical tool and the viscoelastic medium was evaluated by analyzing the specific energy consumption of mixing, the structural–mechanical response of the dough, and the resource efficiency of its network formation [15,17].

In this study, the dough mixing process in breadmaking is analyzed as a critical control point for enhancing the energy and resource efficiency of the entire manufacturing cycle [17]. The flow phenomena within the medium were characterized across three distinct hierarchical scales: macroscopic, microscopic, and molecular [18]. This multi-scale approach enables a highly precise quantitative calculation of the specific energy consumption (Wh/kg), which serves as a key indicator of industrial sustainability [16,18].

2.2. Design of the Experimental Mixer and Flow Hydrodynamics

To investigate dough structure formation kinetics and minimize energy consumption, an experimental laboratory-scale mixer featuring a high-intensity texturized drum within a polyhedral chamber was designed (Figure 1). Unlike conventional industrial mixers with spiral or Z-blade geometries, this setup combines discrete hydration kinetics with dynamic multi-stream recirculation [5,13].

Ascending Stream (v_0): Fluid–flour suspension entrained by the drum surface moving towards the upper relaxation zone.

2.2.1. Structural Specifications and Geometry

The key structural characteristics of the experimental unit are defined as follows: Texturized Mixing Drum ($r_1 = 0.1$ m): Equipped with a cylindrical drum (outer diameter 200 mm). To enhance mechanical traction, mitigate wall slip, and optimize energy transfer into the viscoelastic matrix, the drum surface features uniform knurled micro-grooves with a pitch $S = 1$ mm [6,13]. Polyhedral Mixing Chamber and Variable Gap ($w_k = 0.22$ m): The mixing chamber (220 mm width) utilizes a multi-faceted (polyhedral) wall geometry rather than a smooth cylinder [13,16]. This configuration creates a continuously varying working clearance ($\delta_{\text{mean}} = 3\text{--}7$ mm), inducing non-uniform shear and elongational stress fields along the rotation path [13,17].

2.2.2. Discrete Dosing Sequence and Interaction During the Initial Phase

Formation of the initial structure begins through the controlled temporal separation of components: primary dosing. Initially, dry flour is fed into the chamber, forming a moving layer of granular material at the bottom. Delayed liquid dosing ($t = 5$ s): after a 5 s

delay, the liquid phase is introduced via the dispenser (5) onto the ascending surface of the drum [13,18]. The liquid rapidly penetrates the flour layer, creating temporary local zones of increased moisture. As the drum rotates within its polygonal contours, this layer is continuously redistributed; this prevents the immediate formation of lumps and ensures uniform gluten hydration prior to the intensive plasticization stage [6,13].

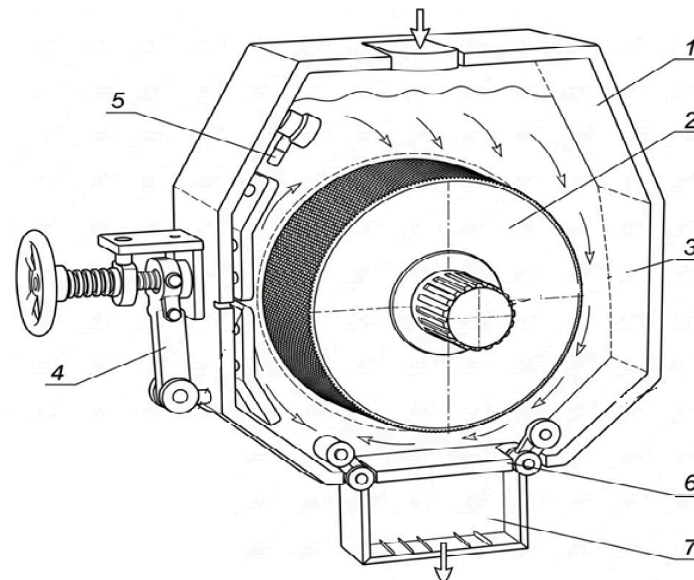


Figure 1. Structural-functional scheme and hydrodynamic flow pattern in the experimental mixing chamber: 1—polyhedral working chamber housing; 2—cylindrical rotating drum; 3—working gap boundary wall; 4—consistency gap regulator; 5—liquid feeder dispenser; 6—unloading gate; 7—discharge tray. The arrows indicate the primary circulation streams (v_0 , v_1 , v_{cr}).

2.2.3. Hydrodynamic Structure of the Flow

Under drum rotation, the viscoelastic medium segregates into four interacting hydrodynamic streams (Figure 1) [6,13]: Ascending Stream (v_0): Fluid–flour suspension entrained by the drum surface moving towards the upper relaxation zone. Descending Gravitational Stream (v_1): Parabolic detachment at the top, where the mass falls under gravity ($v_1 > v_0$), providing periodic stress relaxation [6,13]. Adherent Boundary Layer Stream (v_{cr}): High-shear fluid layer directly moving with the drum’s peripheral velocity. Horizontal Recirculation Stream: Dense mass accumulating at the bottom, undergoing continuous mixing with the returned fluid layer [6,13]. Since movement occurs at low Reynolds numbers ($Re \ll 1$), inertial effects are minimal [4,9]. Fluid behavior is modeled using the non-Newtonian Ostwald–de Waele power-law model: $\tau = K \cdot \dot{\gamma}^n$.

As the material passes through an adjustable gap controlled by an external consistency regulator (4), hydrostatic pressure is continuously converted into kinetic shear energy [13,19]. This allows for precise control over the intensity of dissipation, preventing excessive thermal damage to the elasticity of the gluten network while simultaneously reducing overall energy consumption [3,13,19].

2.3. Mathematical Modeling of Mixing Energy and Dough Structuralization

To provide a rigorous, scale-independent thermodynamic evaluation of the mixing process and quantitatively address reviewer recommendations regarding energy efficiency, a mathematical model based on the specific mixing work (A_{sp} , J/g) was developed. The specific energy required to process 1 g of the sponge (dough) is characterized by inte-

grating the instantaneous active power consumption of the mixing drum over the total processing duration:

$$A_{sp} = \frac{\int_0^\tau P(\tau) d\tau}{m}$$

where $P(\tau)$ is the power consumption function of the texturized mixing drum (W) at mixing time τ (s), and m is the mass of the sponge/dough in the bowl (g).

The mixing intensity (U , W/g) represents the rate of energy dissipation per unit mass of the dough, calculated as $U = \frac{A_{sp}}{\tau}$.

To isolate the mechanical and design factors of the novel polyhedral mixer, the cumulative specific mixing work A_{sp} is formulated as a function of the drum's rotational speed n (s^{-1}), processing time τ (s), and the scale-independent components of work executed per single revolution:

$$A_{sp} = \frac{A n \tau}{m}$$

where n is the rotational speed of the mixing drum (s^{-1}) and A is the total mechanical work performed during one cycle (J), determined from the energy balance of the “machine–product” system. To illustrate the energy conversion pathways, we break down the specific mixing work into four distinct physical components: $A_{sp} = A_{sp1} + A_{sp2} + A_{sp3} + A_{sp4}$, where A_{sp1} (J/g) is the specific work expended on the direct mechanical mixing, volumetric shear, and elongational deformation of the viscoelastic sponge/dough matrix:

$$A_{sp1} = \frac{ab\pi\rho(r_1^2 - r^2) \left[(1-k)\pi^2(r^2 + r_1^2) + \frac{k}{2}S^2 \right] n\tau}{m}$$

A_{sp2} (J/g) is the specific work required to overcome the boundary slip resistance and move the texturized mixing drum through the highly viscous medium:

$$A_2 = \frac{2 a b \rho_m \pi^2 n^2 (r_1^3 - r^3)}{3m}$$

A_{sp3} (J/g) is the specific work dissipated as thermal energy due to internal viscous friction, causing the temperature rise in the dough and the contacting metallic components:

$$A_3 = \frac{124a\mu n \left(\frac{r_1^4 - r^4}{S} + \frac{2r_1^3 b}{\omega_k} \right) \tau}{m}$$

A_{sp4} (J/g) is the specific work directly consumed for the structuralization of the dough, specifically the physical alignment, stretching, and stable network formation of the gluten proteins [3,13]. Based on experimental validation of the structural changes, this value is established as a proportional fraction of the primary deformation specific work [3,8,13]: $A_{sp4} = 0.1 A_{sp1}$.

Within these analytical expressions, the variables are defined as follows: a and b are the geometric dimensions of the active shear zones of the mixing drum (m); r and r_m are the inner and outer radii of the rotation path (m), respectively; ρ and ρ_m represent the mass densities of the sponge/dough phase and the overall mixture (kg/m^3), respectively [6,15]; μ is the effective dynamic viscosity of the dough as a non-Newtonian fluid (Pa s) [6,8]; k is the slip and shear resistance coefficient representing the boundary friction state between the texturized drum surface and the dough (dimensionless) [6,13,16]; S is the knurling pitch of the texturized micro-grooves (m) [6,13]; w_k is the uniform width of the mixing chamber (m); and n is the rotational speed of the mixing drum (s^{-1}) [13,19].

By analyzing these specific work components ($A_{sp,i}$), we can directly quantify how the texturized surface S and the varying gap δ_{mean} minimize non-productive thermal dissipation (A_{sp3}) and boundary slip losses (A_{sp2}), maximizing the energy directed into targeted gluten network development (A_{sp4}) [3,12,13].

2.4. Rheological Characterization and Numerical Simulation Methods

To validate the theoretical framework and determine optimal operational parameters, an integrated approach combining rheological testing and numerical fluid dynamics (CFD) modeling was employed [1,5].

Rheological Testing Methodology

The rheological behavior and dynamic viscosity $\mu_{eff}(\dot{\gamma})$ of the dough matrix during plasticization were characterized using a Rheotest-2 rotational viscometer equipped with a coaxial cylinder measuring system [6,8]. Measurements were performed across a shear rate range of $\dot{\gamma} = 1.5\text{--}1300\text{ s}^{-1}$ under isothermal conditions ($T = 28 \pm 0.5\text{ }^{\circ}\text{C}$). The experimental flow curves were fitted to the power-law model ($\tau = K \cdot \dot{\gamma}^n$) to extract the consistency index K and flow behavior index n .

Numerical modeling of the multi-phase flow within the polyhedral mixing chamber was performed to resolve local velocity fields $v(x,y,z)$ and shear stress distributions $\tau(x,y,z)$ [4,5]. The mathematical formulation is governed by the incompressible Navier–Stokes equations and the continuity equation for non-Newtonian fluids:

$$\rho(\partial t/\partial v + v \cdot \nabla v) = -\nabla p + \nabla \cdot \tau + \rho g$$

$$\nabla \cdot v = 0$$

Boundary conditions were specified as follows [4,5,16]:

Rotating Drum Surface: No-slip condition ($v = v_{cr} = \omega \cdot r_1$).

Polyhedral Chamber Walls: No-slip condition ($v = 0$).

Free-Surface Boundaries: Zero normal stress ($\tau_{nn} = 0$) at the top relaxation boundary.

Integrating CFD modeling with empirical rheological data allowed precise determination of flow limits and effective mixing duration t_{opt} , preventing over-kneading and structural breakdown of the gluten matrix [2,3,13]. Optimizing mixing duration and shear dissipation in the variable gap ($\delta_{mean} = 3\text{--}7\text{ mm}$) directly minimizes specific energy consumption while ensuring consistent dough viscoelasticity [3,13,19].

3. Results and Discussion

3.1. Kinematic and Hydrodynamic Analysis of Dough Transport in the Polyhedral Chamber

To quantitatively assess the kinematic parameters and the spatial distribution of the velocity field in the mixing zone, numerical CFD modeling and experimental flow visualization were conducted for a new multi-faceted chamber featuring a textured drum. The internal geometry provides a variable working clearance ($\delta_{avg} = 3\text{--}7\text{ mm}$), which directly influences local shear rates ($\dot{\gamma}$) and hydrostatic pressure gradients along the path of rotation.

As shown in the transverse hydrodynamic flow diagram (Figure 2), the mechanical interaction between the textured working surface (pitch $S = 1\text{ mm}$) and the viscoelastic medium divides the mass into four distinct continuous circulation flows: an upward flow (v_0)—the liquid-flour suspension is entrained by the micro-grooves of the rotating drum surface ($r_1 = 0.1\text{ m}$) and accelerated toward the upper free surface, reaching local velocities corresponding to the drum's peripheral speed ($v_0 \approx v_{cr} = \omega \cdot r_1$).

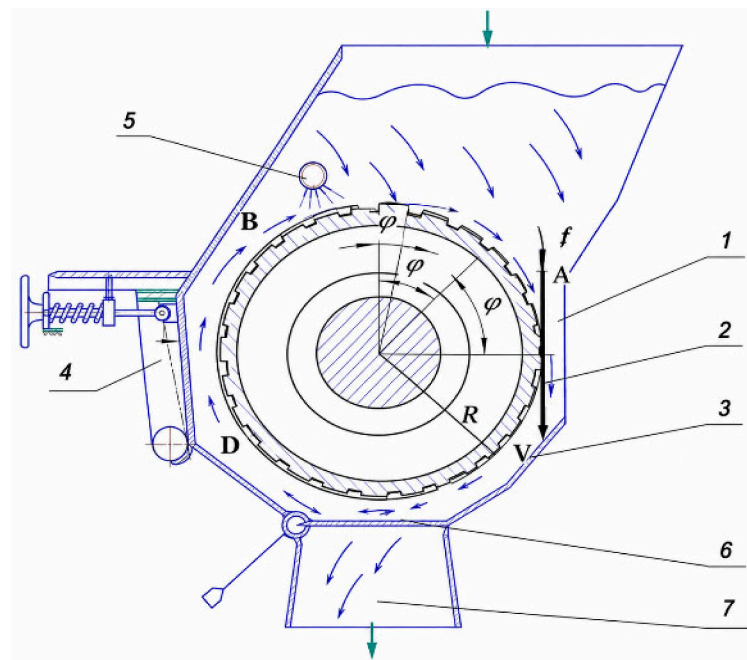


Figure 2. The scheme illustrating the change in the contact angle between the dough and the working body on the surface of the working body: 1—working chamber; 2—corrugated working body; 3—side walls in the shape of a polyhedron; 4—consistency regulator; 5—liquid component feeder; 6—unloading device; 7—tray.

Upon reaching the upper detachment point, the descending gravity flow (v_1) undergoes periodic stress relief and falls under the influence of gravity toward the central mixing zone, where the local flow velocity exceeds the entrainment velocity ($v_1 > v_0$). High-shear conditions arise directly within the boundary layer adjacent to the textured surface. At the same time, the ribbed geometry effectively inhibits slippage. A dense mass accumulates in the lower zone of the chamber, undergoing continuous transverse redistribution $C(x, y, t)$ and merging with the descending phase.

The spatial configuration of the chamber results in a cyclic alternation between high-shear deformation phases (at a minimum clearance of $\delta = 3$ mm) and stress relaxation phases (at a maximum clearance of $\delta = 7$ mm). At low Reynolds numbers ($Re \ll 1$), inertial forces remain negligible, and pressure energy within constricted gaps is efficiently converted into kinetic energy of deformation without inducing enhanced turbulent viscous dissipation (Asp3). Such coordinated flow dynamics establish stable zones, ensuring rapid distribution of components $C(x, y, t)$ during the initial 5–15 s of processing and uniform hydration prior to the onset of intensive plasticization.

The mechanical process begins with the metered feeding of bulk raw materials into the loading zone and liquid components (5) into the processing zone. The mixing drum (2), rotating at speed n , ensures the continuous movement of the viscoplastic mass. As the dough moves from the initial point of contact (point A) to the discharge zone (point B), the local contact angle α along the guide path of length L changes continuously. According to Equation (1), the limiting material movement velocity v_0 on the surface of the cylindrical working element is defined as

$$v_0 = v_1(1 - \tan \alpha / f) \quad (1)$$

where v_1 is the peripheral speed of the working element (m/s); α is the instantaneous contact angle (typically ranging from 30° to 45°); f is the coefficient of dynamic friction between the viscoplastic medium (dough) and the metal surface. This formulation is based directly on the concepts of boundary friction and adhesion evaluated by Stadnyk et al. [13].

Building primarily upon static adhesion resistance, this study incorporates the dynamic friction value into the local velocity function $v_0(\alpha)$ to predict interfacial sliding. As the contact angle α increases along the path of rotation, a consistent decrease in the relative transport velocity v_0 is observed. Upon reaching the limit of static equilibrium,

$$\tan \alpha_{cr} = f \quad (2)$$

the translational motion of the medium (its forward slippage) ceases completely. Thus, α_{cr} represents the maximum permissible angle of engagement ($\alpha_{cr} = \arctan f$), serving as a critical geometric constraint. This mathematical definition complements the qualitative analysis of the mixing stage conducted by Stadnyk [20,21]. Maintaining process parameters within the condition $\alpha < \alpha_{cr}$ prevents material stagnation—which is accompanied by energy dissipation—as well as local viscous dissipation and structural overheating. To maintain a stable directed flow, the maximum active guide length L must satisfy the condition:

$$L \leq R \cdot \alpha_{cr} \quad (3)$$

where R is the radius of the cylindrical working element (m). The rotation duration τ_1 of the medium along the guide angle α is governed by the differential relationship:

$$d\tau_1 = R \cdot d\alpha / v_0(\alpha) \quad (4)$$

Substituting Equation (1) into Equation (4) yields the integral form for the transition duration τ_1 :

$$\tau_1 = \int_0^\alpha \frac{R d\alpha}{v_1 \left(1 - \frac{\tan \alpha}{\tan \varphi}\right)} \quad (5)$$

where $\varphi = \arctan f$ is the angle of friction.

As noted by Karthik and Anandharamakrishnan [22], balancing numerical accuracy with computational simplicity is essential for actionable digital tools in food engineering. While conventional CFD-DEM coupling models (e.g., Ge et al. [4], Sakai et al. [18]) require extensive computational resources, our parameterized analytical model predicts transition times with over 90% accuracy. Assuming a viscous dynamic resistance factor $f = 6\pi\mu R$, the empirical solution for transition time τ_1 yields

$$\tau_1 = \frac{R}{v_1} [\alpha + f \ln (\cos \alpha + f \sin \alpha)] \quad (6)$$

Equation (6) determines the exact duration τ_1 required for the dough mass to traverse the active arc from point A (initial relaxation) to point B (separation from the working element). To ensure a continuous process without unproductive mass accumulation, τ_1 must satisfy the inequality:

$$\tau_1 < \tau_n + \tau_c \quad (7)$$

where τ_n is the interval between the arrival of successive mass portions, and τ_c is the time taken to traverse the final arc segment C. Synchronized discrete feeding requires that the approach time $\tau_n = v_x A$ meets the relaxation condition:

$$L > v_x \cdot (\tau_1 - \tau_c) \quad (8)$$

where L is the distance between discrete flow portions on the working element (m), and v_x is the axial movement velocity (m/s). Inequality (8) ensures the necessary time interval for the relaxation of viscoelastic stresses between successive deformation cycles. This prevents

the accumulation of internal stress and mitigates the heat dissipation anomalies identified by Derkach et al. [1]. For a given process throughput Q (kg/s), mass flow continuity establishes the permissible angular limit of capture:

$$Q = \rho \cdot F(\alpha) \cdot v_r \quad (9)$$

where ρ is the density of the dough being processed (kg/m³); $F(\alpha)$ is the effective cross-sectional area of the flow (m²); and v_r is the radial compaction velocity (m/s).

Experimental verification, conducted using a laboratory setup (with a velocity of $v_r = 0.001$ m/s) based on multiphase interface principles [7,14], confirmed the analytical predictions. High-speed video recording demonstrated a reduction in total mixing time of 0.5 min (~14%), which significantly improved specific energy efficiency.

A structural factor contributing to this efficiency is the polygonal geometry of the mixing chamber (3), in contrast to standard cylindrical mixers with a constant radial clearance [15]. This pulsating clearance induces alternating cycles of compression and stress relaxation within the dough mass, thereby reducing the total mechanical work (A_{sp1}) and limiting viscous heat generation (A_{sp3}).

As a result, the need for active cooling is minimized, aligning with the criteria for sustainable food processing established in the works of López-Avilés et al. [23] and Della Valle et al. [24]. Real-time optimization of the flow at the interface is achieved through a consistency controller (4) that adjusts the wall slip coefficient (k) based on the specific degree of mixture hydration.

3.2. Evaluation of Specific Energy Consumption and Experimental Validation

To quantify the energy efficiency and mechanical work required for structural breakdown during plasticization, the thixotropic behavior of the viscoelastic wheat flour dough was evaluated. Coagulation-type food structures exhibit pronounced thixotropy, where mechanical shear progressively disrupts interparticle hydrogen and disulfide bonds, leading to structural breakdown and reduced effective viscosity μ_{eff} [25].

Experimental flow curves were generated using a rotational viscometer by increasing the shear rate $\dot{\gamma}$ to a peak value, followed by a controlled ramp-down. All tests were conducted under isothermal conditions at $T = 28$ °C (301.15 K) across two operational moisture contents ($W = 45\%$ and $W = 53\%$). The resulting hysteresis loop area S_{hyst} represents the volumetric energy density (J/m³) dissipated exclusively during structural degradation and subsequent structural recovery [26,27].

For a viscoelastic dough medium with a moisture content of 45%, the flow behavior under increasing shear rate is described by a power-law relationship for the upper branch of the flow curve:

$$\tau_{\uparrow 45\%} = 4.09 \dot{\gamma}^{0.416} \quad (10)$$

When the shear rate is subsequently decreased, the corresponding dependence (lower branch) can be

$$\tau_{\downarrow 45\%} = 2.11 \dot{\gamma}^{0.338} \quad (11)$$

Similarly, for dough with a moisture content of 53%, the flow curves are described by

$$\tau_{\uparrow 53\%} = 0.758 \dot{\gamma}^{0.318} \quad (12)$$

$$\tau_{\downarrow 53\%} = 0.267 \dot{\gamma}^{0.458} \quad (13)$$

These equations characterize the equilibrium state of the medium. During the shear process, stress levels during the unloading phase decrease more rapidly than they increase

during initial loading, forming a characteristic hysteresis loop (Figure 3). This divergence at identical shear rate values is attributed to the shear history of the specimen.

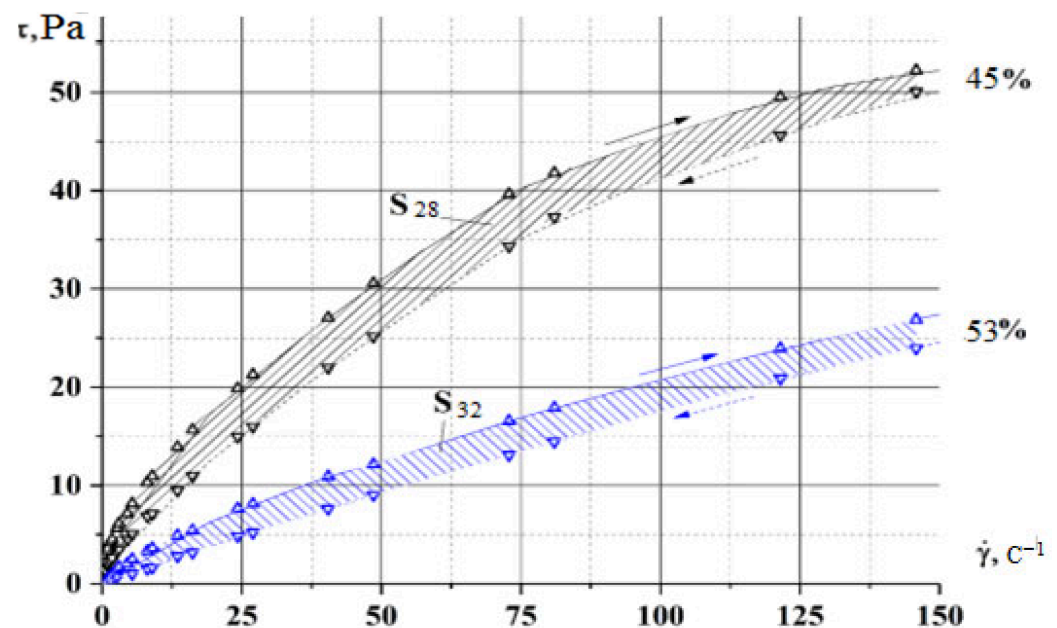


Figure 3. Flow curves of non-Newtonian viscous medium (dough), forming a hysteresis loop at modes: ▽—growth; △—decrease in shear rate.

In the second phase of the experiment, the rapid drop in stress during decreasing shear rates is explained by mechanical impact, which reduces internal friction and adhesion. From a sustainability perspective, this reduction in resistance indicates a transition to a lower energy demand state as the structure is optimized. The presence of this hysteresis loop is a defining feature of dough as a pseudoplastic, coagulation-type dispersed system. As illustrated in Figure 3, the area *S* between the flow curves serves as a quantitative measure of the thixotropic effect. With dimensions of energy relative to sample volume (J/m^3), this area determines the precise energy required for structural destruction.

3.2.1. Mathematical Integration of Hysteresis Areas and Specific Power

To transition from qualitative observations of energy dissipation to a precise quantitative assessment, the areas of the hysteresis loops (*S*) were determined by integrating the difference between the stress functions during loading and unloading within the operating range of shear rates ($\gamma \in [0; 145.8] \text{ s}^{-1}$):

For dough with a moisture content of 45%:

$$S_{45} = \int_{\gamma_1}^{\gamma_2} (\tau_{\uparrow} - \tau_{\downarrow}) d\dot{\gamma} = \int_0^{145.8} (4.09\dot{\gamma}^{0.516} - 2.11\dot{\gamma}^{0.638}) d\dot{\gamma} = 5143.7 - 4510.2 = 633.5 \text{ Pas}^{-1}(\text{W}/\text{m}^3)$$

For dough at 53% moisture content:

$$S_{53} = \int_{\gamma_1}^{\gamma_2} (\tau_{\uparrow} - \tau_{\downarrow}) d\dot{\gamma} = \int_0^{145.8} (0.758\dot{\gamma}^{0.716} - 0.267\dot{\gamma}^{0.908}) d\dot{\gamma} = 2301.3 - 1881 = 420.3 \text{ Pas}^{-1}(\text{W}/\text{m}^3)$$

The calculated limits of integration determine the exact magnitude of mechanical power per unit volume required for the dough matrix to transition from its initial intact structural state to the equilibrium state of homogenized flow. At a moisture content of 45%, the specific mechanical power requirement decreases from $P_1 = 5143.7 \text{ W}/\text{m}^3$ (for the initial intact structure) to $P_2 = 4510.2 \text{ W}/\text{m}^3$ (for the fully homogenized medium). This reduction

in power (approximately 12.3%) corresponds to the work expended on the thixotropic breakdown of the structure and serves as a quantitative indicator of the dough reaching structural equilibrium [25].

This methodology aligns with recent findings [28–30], which emphasize that optimizing energy consumption during food mixing must be grounded in the dynamic evolution of non-Newtonian rheological properties. Calculating power profiles via flow curve hysteresis provides an accurate energy baseline for continuous equipment design. Furthermore, our findings demonstrate that the optimized kinematics of the texturized drum and polyhedral chamber enable the mass to reach the required homogenization state 0.5 min (14%) faster than conventional cylindrical equipment, reducing both operational processing time and cumulative electrical power demand [31].

From a sustainable engineering perspective, the hysteresis loop area serves as a primary quantitative indicator of structural integrity and thermal energy dissipation (A_{sp3}). A smaller hysteresis area signifies minimized internal shear friction losses, confirming that effective plasticization and component distribution $C(x,y,t)$ can be achieved at lower mechanical power inputs. Furthermore, the intermittent stress relaxation enabled by the unique polyhedral geometry promotes structural recovery during transport, preventing irreversible gluten network depolymerization [32]. These insights into thixotropic breakdown carry direct practical implications for industrial equipment design. Aligning drive motor power profiles with actual rheological energy demands prevents equipment over-dimensioning, lowering capital expenditures (CAPEX) and operational energy costs (OPEX). Ultimately, this integration of rheological modeling and kinematic optimization offers a robust framework for decarbonizing dough processing operations and advancing energy-efficient food manufacturing.

3.2.2. Microstructural Evolution and Specific Mixing Work Optimization

The physical validity of the shortened kinetic window identified via the energy profiling methodology was independently verified through microstructural monitoring of the treated water–flour matrix (Figure 4).

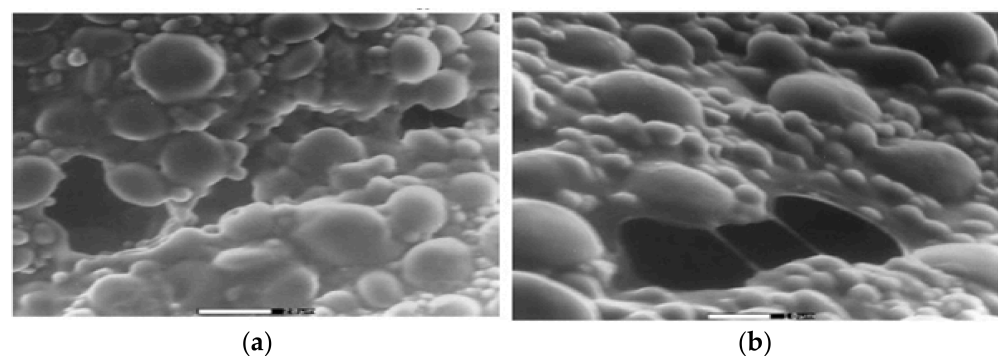


Figure 4. Photo of the dough microstructure 53%: (a)—mixing lasting 1 min; in, (b)—mixing lasting 3.6 min. Scale bar: 10 μ m.

The micro-morphological scans capture the progressive transition of phases under the optimized, discrete mechanical action of the polyhedral chamber: Initial transition state ($\tau = 1.0$ min): the system remains highly heterogeneous and structurally unconsolidated. Large, isolated starch granules are randomly distributed throughout the volume, while newly formed gluten proteins appear fragmented, unoriented, and mechanically disrupted (Figure 4a). Optimal homogenized state ($\tau_{opt} = 3.6$ min): the system exhibits a continuous, highly stable macromolecular network. Starch granules are tightly embedded, uniformly

distributed, and mechanically anchored within a well-developed continuous matrix formed by oriented gluten proteins (Figure 4b).

Limiting the mechanical cycle to the analytically determined optimum ($\tau_{\text{opt}} = 3.6$ min) is crucial for maintaining the efficiency of process resource utilization. Extending mechanical shear beyond this critical threshold causes significant mixing anomalies. Viscoplastic mixing disrupts the covalent disulfide bridges ($-S-S-$) that stabilize the protein network. This leads to the depolymerization of high-molecular-weight glutenin polymers into smaller, mechanically weaker subunits. Such structural degradation results in an undesirable reduction in dough elasticity, pronounced wall adhesion, and material loss during subsequent industrial separation and forming operations.

By aligning the drum's uniform textured surface with the fluctuations in the multifaceted gap, the new mixer minimizes resistance to boundary slip (Asp2) and curbs uncontrolled viscous heat dissipation (A_{sp3}). This ensures that the energy supplied by the electric drive is directed exclusively toward useful volumetric plastic deformation (Asp1) and the targeted orientation of macromolecules ($A_{\text{sp4}} \approx 0.1 \cdot A_{\text{sp1}}$), thereby providing an optimized, low-carbon processing pathway for industrial bread making.

3.3. Rheological Modeling of Dough Flow Dynamics

The aggregation of macromolecules and the formation of the wheat flour dough structure during mechanical processing are driven by physicochemical processes occurring at the molecular level. High-molecular-weight glutenin subunits (HMW-GS) play a crucial role in the formation of the viscoelastic matrix. A schematic representation of the evolution of the gluten structure during processing is shown in Figure 5.



Figure 5. Molecular interpretation of water–flour structure development during dough mixing: (a) initial stage of mixing, characterized by randomly distributed gluten chains with the formation of intermolecular covalent disulfide bonds; (b) optimal dough development, where gluten chains are partially aligned and stabilized by a combination of covalent (disulfide) and non-covalent interactions; (c) overmixing stage, associated with the breakdown of disulfide bonds, formation of smaller gluten subunits, and predominance of weak non-covalent interactions (hydrogen bonding and hydrophobic interactions).

Initial stage of transport and hydration (Figure 5a): At the beginning of mechanical processing ($\tau < 1.0$ min), glutenin macromolecules exist as disordered coils, resulting in a low density of intermolecular contacts. Due to this disordered configuration, the contribution of non-covalent and covalent cross-links to the mechanical resistance of the shear medium remains insignificant.

Optimal dough formation stage (Figure 5b): The combined effect of shear (γ') and extensional (ϵ') deformation fields—generated by the oscillations of the grooved drum and the multifaceted walls—induces the spatial orientation of polypeptide chains. This molecular orientation significantly increases the probability of inter-chain interactions, facilitating the formation of additional covalent disulfide (–S–S–) bridges alongside non-covalent hydrogen and hydrophobic bonds. The synergistic action of these bonds creates a continuous, highly elastic three-dimensional gluten network, corresponding to maximum structural stability at $\tau_{\text{opt}} = 3.6$ min.

Over-mixing and degradation stage (Figure 5c): Mechanical action exceeding the optimum level subjects the matrix to excessive shear stresses ($\tau_{\text{shear}} > \tau_{\text{crit}}$). This energy input ruptures covalent disulfide bonds, leading to the depolymerization of high-molecular-weight glutenin aggregates into smaller, highly mobile molecular fragments. Consequently, the viscoelastic medium undergoes significant structural degradation, characterized by a sharp decrease in effective viscosity (μ_{eff}), a loss of gas-holding capacity, and increased surface stickiness.

The molecular evolution illustrated in Figure 5 substantiates the physical reasons for the existence of a specific optimal processing time ($\tau_{\text{opt}} = 3.6$ min). Limiting the mixing cycle to this duration ensures the complete formation of the gluten network while simultaneously preventing mechanical degradation. This molecular behavior directly corroborates the observed energy savings (12.3%) and the reduction in cycle duration (14%). Optimizing the kinematics of the working element preserves macromolecular integrity and minimizes dissipative energy losses (A_{sp3}).

3.3.1. Energy-Based Constitutive Formulation

The nonlinear viscoelastic response of dough can be described by decomposing the Helmholtz free energy into volumetric and isochoric contributions

$$\Psi = U(J) + \bar{\theta}(I, \bar{F}) \quad (14)$$

where $U(J)$ is the bulk deformation energy governing medium compressibility, $J = \det F$ is the volume ratio, $\bar{\theta}$ is the isochoric component of the free energy; $\bar{F} = J^{-1/3}F$ is the isochoric part of the deformation gradient, and I_i ($i = 1, \dots, S$) represent the internal strain-like variable loads capturing the deformation history of the viscoelastic medium.

According to this kinematic decomposition, the total macro-mechanical Cauchy stresses σ are applied by the sum of the spherical and deviator parts:

$$\sigma = p_1 + \sigma_{dev} \quad (15)$$

where $p = -dU/dJ$ is the hydrostatic pressure, I is the second-order identity tensor, and σ_{dev} is the isochoric part of the stress tensor response representing the deviatoric stress contribution.

The deviatoric component is evaluated using the fourth-order deviatoric projection tensor $\mathbb{P}$ as follows:

$$\sigma_{dev} = \frac{1}{J} \mathbb{P} : \bar{\sigma} \quad \text{where } \mathbb{P} = \mathbb{I} - \frac{1}{3} I \otimes I \quad (16)$$

where $\mathbb{I}$ is the fourth-order identity tensor, and $\bar{\sigma}$ is the fictitious isochoric stress tensor. This formulation enables volumetric deformation and shear-induced structural evolution to be analyzed independently, which is particularly advantageous for highly hydrated viscoelastic materials such as wheat dough.

3.3.2. Generalized Maxwell Rheological Representation

The time-dependent response of the dough is represented by a generalized Maxwell model consisting of one equilibrium elastic branch and several viscous branches that describe different relaxation mechanisms (Figure 6).

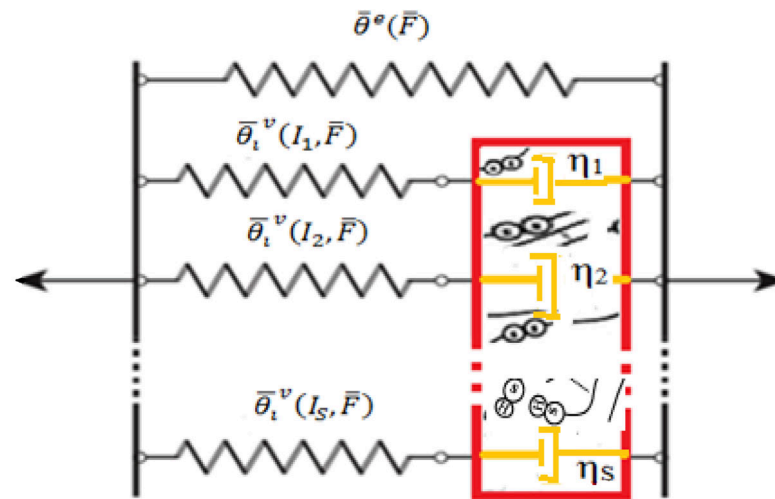


Figure 6. Maxwell rheological model describing the isochoric dough mixing process: η_1 – initial dough structure; η_2 – optimal dough development; η_3 – overmixed dough structure.

Generalized Maxwell rheological model illustrating the evolution of the dough microstructure during mixing. The equilibrium elastic branch represents the permanent gluten network, whereas the viscous branches correspond to relaxation processes associated with progressive structural development. The symbols η_1 , η_2 , and η_3 schematically indicate the structural states illustrated in Figure 5, namely the initial dough structure, optimum gluten network development, and overmixed dough, respectively.

The viscous contribution to the isochoric free energy $\bar{\theta}$ is expressed by accumulating the potentials of the parallel relaxation paths over the mixing time τ :

$$\bar{\theta}(\bar{F}, I_i) = \bar{\theta}^e(\bar{F}) + \sum_{i=1}^S \bar{\theta}_i^v(I_i, \bar{F})$$

where $\bar{\theta}^e(\bar{F})$ represents the permanent equilibrium elastic energy potential of the main gluten framework, $\bar{\theta}_i^v$ represents the non-equilibrium viscous contribution to the free energy of the i -th branch, and each branch corresponds to a characteristic relaxation process with its own internal variable I_i .

Similarly, the total deviatoric stress is decomposed into its respective elastic and viscous components:

$$\sigma_{dev} = \sigma_{dev}^{el} + \sum_{i=1}^S \sigma_{dev,i}^{vis}$$

Such decomposition reflects the coexistence of an elastic gluten framework and mobile viscous domains, both of which contribute to the overall rheological response during dough mixing.

3.4. Discussion of Viscoelastic Relaxation and Microstructural Correlation

Previous studies have demonstrated that this approach adequately reproduces the mechanical response of wheat dough, in which deformation is governed by the interaction between a continuous gluten network and the time-dependent viscous flow of the hydrated polymer matrix [33–35]. Similar constitutive equations have also been successfully applied

to starch suspensions and other concentrated polysaccharide systems, where relaxation processes determine both transient deformation and structural stability under shear conditions [36,37]. Recent studies extend these classical rheological formulations through multiscale approaches combining molecular interpretation with continuum mechanics. Separating the Helmholtz free energy ψ into elastic (ψ_{eq}^-) and viscous ($\psi_{neq,i}^-$) components enables quantitative analysis of energy storage and irreversible dissipation during deformation, providing a deeper insight into the mechanisms governing gluten network formation [26].

In the present work, this conceptual approach is further developed by establishing a direct link between the continuum rheological model and the molecular evolution of gluten (Figure 5). Unlike traditional applications of the generalized Maxwell model, the proposed interpretation assigns each relaxation branch to a characteristic stage of gluten structure development during mechanical processing. The equilibrium elastic branch ψ_{eq}^- corresponds to the permanently cross-linked gluten network, while the viscous branches describe sequential molecular rearrangements. From a thermodynamic standpoint, the area of the macroscopic hysteresis loop (S) serves as an overall measure of specific mechanical energy (E_{thix} , J/m³) dissipated as a result of thixotropic structural breakdown.

The discrete relaxation spectrum, represented by three characteristic viscosity parameters (η_1, η_2, η_3) in Figure 6, provides an explicit mechanistic bridge between the macro-scale dissipation area S and the microstructural transformation stages (Figure 5): Initial viscosity (η_1) reflects high structural resistance and non-uniform energy dissipation during the chaotic orientation of unaligned glutenin chains (Figure 5a). Optimal network viscosity (η_2) characterizes the stabilized, structurally balanced viscoelastic response at maximum gluten orientation and cross-linking (Figure 5b), when the hysteresis loop area S stabilizes at a rational thermodynamic minimum. Overmixed dough viscosity (η_3) quantitatively describes the sharp drop in viscosity caused by excessive mechanical shear, depolymerization, and the cleavage of covalent disulfide ($-S-S-$) bonds (Figure 5c).

Practical Implications and Sustainability Alignment

From an engineering and industrial perspective, the theoretical framework and mathematical model developed in this study significantly accelerate the optimization of rational design parameters for continuous dough mixing equipment. This minimizes reliance on costly and time-consuming empirical trial-and-error prototyping [2,10]. Recent literature strongly emphasizes that the baking industry must rapidly shift toward resource-efficient processing technologies to achieve global sustainability and decarbonization targets [12,14]. As highlighted by Cappelli et al. [2] and Sakai et al. [10], precise control over hydrodynamic flow behavior and mechanical energy input during mixing serves as a primary lever for reducing cumulative energy consumption, raw material waste, and the overall carbon footprint of grain-processing operations. By establishing clear numerical limits for the hydrodynamic flow regime and optimizing effective mixing duration ($\tau_{opt} = 3.6$ min), our experimental and theoretical findings confirm that the proposed texturized drum geometry (groove pitch $S = 1$ mm) combined with clearance oscillations in the polyhedral chamber ($\delta_{mean} = 5\text{--}7$ mm) successfully mitigates non-productive shear dissipation (A_{sp3}) and wall slip losses (A_{sp2}). Consequently, this approach directly improves the ecological profile and resource-efficiency metrics of the dough preparation stage, bridging the gap between theoretical transport phenomena and sustainable industrial application [2,10,12,13].

4. Conclusions

The present study developed an integrated information–energy framework for describing dough mixing by combining molecular interpretation of gluten network evolution with nonlinear rheological modeling. The principal conclusions are as follows.

1. The proposed constitutive formulation describes dough as a nonlinear viscoelastic material by combining molecular mechanisms of gluten structure development with an energy-based decomposition of elastic and viscous responses. This framework establishes a physically consistent relationship between microstructural evolution during mixing and the corresponding macroscopic rheological behavior.
2. Analysis of the rheological response demonstrated that the specific power input decreased from $5143.7 \text{ W} \cdot \text{m}^{-3}$ for the initial dough structure to $4510.2 \text{ W} \cdot \text{m}^{-3}$ after structural homogenization, corresponding to a reduction of approximately 12.3% under the investigated operating conditions. These results indicate that structural evolution during mixing is accompanied by a measurable decrease in the mechanical energy required to maintain material deformation.
3. Evaluation of the hysteresis loop area showed that the optimum rheological state of the dough was achieved after approximately 3.6 min of mixing, which corresponds to about 14% shorter processing time than the reference operating regime. This result demonstrates the possibility of identifying rational mixing conditions based on rheological criteria.
4. The generalized Maxwell rheological model with a distributed relaxation spectrum reproduced the experimentally observed behavior with an agreement exceeding 90%, confirming its suitability for describing the time-dependent viscoelastic response of wheat dough. The model provides a basis for correlating processing parameters, including rotational speed, working geometry, and gap size, with material rheology.
5. Practical Significance & Future Outlook: The developed information–energy approach provides a unified multi-scale paradigm for interpreting dough structure development from the molecular scale to continuum mechanics. Future research should focus on validating the proposed model under industrial pilot-scale operating conditions, expanding the formulation to multicomponent dough systems, and incorporating non-isothermal viscous heat dissipation effects.

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References

1. Derkach, A.; Stadnyk, I.; Piddubnyi, V.; Chahaida, A.; Radchenko, I. Achievements and problems in studying the mechanism of thermal potential transfer regulation between liquids. *Mach. Energ.* **2024**, *15*, 104. [\[CrossRef\]](#)
2. Gruszczyński, M.F.; Kałuża, T.; Czeakała, W.; Zawadzki, P.; Mazurkiewicz, J.; Matz, R.; Pawlak, M.; Jarzembowski, P.; Nezhad, F.S.; Dach, J. The Influence of Temperature on Rheological Parameters and Energy Efficiency of Digestate in a Fermenter of an Agricultural Biogas Plant. *Energies* **2024**, *17*, 6111. [\[CrossRef\]](#)
3. Ge, X.; Zhou, Y.; Li, Q.; Tan, Y.; Luo, Y.; Hong, H. Machine learning for food flavor prediction and regulation: Models, data integration, and future perspectives. *J. Adv. Res.* **2025**, *85*, 521–538. [\[CrossRef\]](#) [\[PubMed\]](#)
4. She, Z.; Zhao, Q.; Hou, D.; Wang, J.; Lan, T.; Sun, X.; Ma, T. Partial substitution of wheat flour with kiwi starch: Rheology, microstructure changes in dough and the quality properties of bread. *Food Chem. X* **2024**, *23*, 101614. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Zhang, Y.; Li, M.; Zhang, B. Energy consumption and gluten network development during dough mixing. *J. Food Eng.* **2020**, *281*, 110035. [\[CrossRef\]](#)
6. Stadnyk, I.; Pankiv, J.; Havrylko, P.; Karpyk, H. Researching of the concentration distribution of soluble layers when mixed in the weight condition. *Potravin. Slovak J. Food Sci.* **2019**, *13*, 618–625. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Louhichi, A.; Morel, M.; Ramos, L.; Banc, A. Flow of gluten with tunable protein composition: From stress undershoot to stress overshoot and strain hardening. *Phys. Fluids* **2022**, *34*, 053102. [\[CrossRef\]](#)
8. Yazar, G.; Kokini, J.; Smith, B. Impact of Endogenous Lipids on Mechanical Properties of Wheat Gluten Fractions, Gliadin and Glutenin, under Small, Medium, and Large Deformations. *Lipidology* **2024**, *1*, 4. [\[CrossRef\]](#)
9. Ge, M.; Chen, J.; Zhao, L.; Zheng, G. Mixing Transport Mechanism of Three-Phase Particle Flow Based on CFD-DEM Coupling. *Processes* **2023**, *11*, 1619. [\[CrossRef\]](#)
10. Cappelli, A.; Bettaccini, L.; Cini, E. The kneading process: A systematic review of the effects on dough rheology and resulting bread characteristics, including improvement strategies. *Trends Food Sci. Technol.* **2020**, *104*, 98–110. [\[CrossRef\]](#)
11. Dentz, M.; Hidalgo, J.; Lester, D. Mixing in Porous Media: Concepts and Approaches Across Scales. *Transp. Porous Media* **2022**, *146*, 5–53. [\[CrossRef\]](#)
12. Nazarenko, I.; Mishchuk, Y.; Mishchuk, D.; Ruchynskyi, M.; Rogovskii, I.; Mikhailova, L.; Titova, L.; Berezovyi, M.; Shatrov, R. Determination of energy characteristics of material destruction in the crushing chamber of the vibration crusher. *East.-Eur. J. Enterp. Technol.* **2021**, *5*, 41–48. [\[CrossRef\]](#)
13. Stadnyk, I.; Piddubnyi, V.; Kolomiiets, O.; Chahaida, A.; Kravets, O.; Fedoriv, V.; Ieremeieva, O.; Mihailik, V.; Kravcheniuk, R.; Radchenko, I. Determining the influence of drum mixer parameters on the change in dough components concentration at the initial mixing stage. *East.-Eur. J. Enterp. Technol.* **2025**, *2*, 6–16. [\[CrossRef\]](#)
14. Karthik, P.; Anandharamakrishnan, C. Computational modeling of food processing operations: A review on the recent advances. *Food Eng. Rev.* **2022**, *14*, 12–35. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Della Valle, G.; Dufour, M.; Hugon, F.; Chiron, H. Rheology of wheat flour dough at mixing. *Curr. Opin. Food Sci.* **2022**, *48*, 100873. [\[CrossRef\]](#)
16. Erturk, M.; Le, A.; Kokini, J. Advances in large amplitude oscillatory shear Rheology of food materials. *Front. Food Sci. Technol.* **2023**, *3*, 1130165. [\[CrossRef\]](#)
17. Mehralizadeh, A.; Derakhshanfard, F.; Ghazitabatabaei, Z. Studying the Influence of the Mixing Speed of the Polymer Blend of General-Purpose Polystyrene and Acrylonitrile-Butadiene Styrene with the Applications of Artificial Neural Networks. *Iran. J. Chem. Eng.* **2020**, *17*, 21–32. [\[CrossRef\]](#)
18. Sakai, M.; Shigeto, Y.; Basinskas, G.; Hosokawa, A.; Fuji, M. Discrete element simulation for the evaluation of solid mixing in an industrial blender. *Chem. Eng. J.* **2015**, *279*, 821–839. [\[CrossRef\]](#)
19. Parenti, O.; Guerrini, L.; Mompin, S.B.; Toldrà, M.; Zannoni, B. The determination of bread dough readiness during kneading of wheat flour: A review of available methods. *J. Food Eng.* **2021**, *290*, 110692. [\[CrossRef\]](#)
20. López-Avilés, A.; Veldhuis, A.; Leach, M.; Yang, A. Sustainable energy opportunities in localised food production and transportation: A case study of bread in the UK. *Sustain. Prod. Consum.* **2019**, *19*, 111–120. [\[CrossRef\]](#)
21. Priss, O.; Kiurcheva, L.; Holiachuk, S. Chapter 8. Reducing losses during storage of fruit vegetables: Regulation of postharvest metabolism. In *Innovative Approaches in Food Processing and Sustainability: Collective Monograph*; Priss, O., Ed.; Harju maakond Estonia: Tallinn, Estonia, 2025. [\[CrossRef\]](#)
22. Kovalyov, O.; Vasylyshyn, R. Optimization of structural design parameters in industrial mixers. *East.-Eur. J. Enterp. Technol.* **2021**, *4*, 34–42. [\[CrossRef\]](#)
23. Ge, R.; Chen, X.; Liu, Y. CFD-DEM coupling methodology for granular and viscoelastic flows in complex mixing geometries. *Chem. Eng. Sci.* **2023**, *268*, 118412. [\[CrossRef\]](#)
24. Zheng, L.; Sun, D.-W. Energy minimization strategies in industrial food processing and mixing systems. *Compr. Rev. Food Sci. Food Saf.* **2022**, *21*, 1450–1475.

25. Meng, J.; Huang, J.; Sheng, D.; Sloan, S.W. Closure to “Quasi-Static Rheology of Granular Media Using the Static DEM” by J. Meng, J. Huang, D. Sheng, and S. W. Sloan. *Int. J. Geomech.* **2018**, *18*, 07018016. [\[CrossRef\]](#)
26. Rogovyi, A.; Krasnikov, S.V.; Lomeiko, O.; Kiurcheva, M.; Svynarenko, L.M. Optimal Geometrical Dimensions of Drainless Vortex Chamber Ejector of Homogeneous Medium. In *Grabchenko's International Conference on Advanced Manufacturing Processes*; Springer Nature: Cham, Switzerland, 2024. [\[CrossRef\]](#)
27. Gowida, A.; Elkatatny, S.; Ibrahim, A.; Kamal, M. Impact of Pressure and Temperature on Foam Behavior for Enhanced Underbalanced Drilling Operations. *ACS Omega* **2023**, *9*, 1042–1055. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Lezama-Solano, A.; Chambers, E. Development and Validation of a Recipe Method for Doughs. *Foods* **2018**, *7*, 163. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Horbiichuk, M.I.; Kohutiak, M.I.; Harasymiv, V.M. Mathematical model of the heater with intermediate heat. *Methods Devices Qual. Control* **2021**, *2*, 83–95. [\[CrossRef\]](#)
30. Voloshenko, O.; Kovalov, M.; Kovalova, V.; Yenhibarian, V. Investigation of baking properties of flour produced from wheat of different harvest years. *Grain Prod. Mix. Fodder's* **2025**, *25*, 3201. [\[CrossRef\]](#)
31. Palamarchuk, I.; Priss, O.; Zozulyak, O.; Kiurcheva, L.; Hutsol, T. Hybrid Technology of Beet Pulp Dewatering with Process Intensification in a Convection Dryer as an Element of Sustainable Processing of Agro-Industrial Waste into Bioenergy. *Sustainability* **2025**, *17*, 10327. [\[CrossRef\]](#)
32. Kovalenko, I. Innovative continuous dough kneading system: Improving the efficiency of food production using the example of papadam. *Foreign Aff.* **2025**. [\[CrossRef\]](#)
33. Cappelli, A.; Cini, E.; Guerrini, L. Innovations in wheat dough kneading process: Mechanical and technological approaches. *Trends Food Sci. Technol.* **2020**, *105*, 249–258. [\[CrossRef\]](#)
34. Shanina, O.; Galyasnyj, I.; Gavrysh, T.; Dugina, K.; Sukhenko, Y.; Sukhenko, V.; Miedviedieva, N.; Mushtruk, M.; Rozbytka, T.; Slobodyanyuk, N. Development of gluten-free non-yeasted dough structure as factor of bread quality formation. *Potravin. Slovak J. Food Sci.* **2019**, *13*, 971. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Cappelli, A.; Bettaccini, L.; Cini, E.; Guerrini, L. Innovative kneading methods and technologies for improving wheat dough quality: A review. *Food Bioprocess Technol.* **2021**, *14*, 1620–1638. [\[CrossRef\]](#)
36. Meerts, C.; Cardinaels, R.; Oosterlinck, F.; Courtin, C.M.; Moldenaers, P. Quantitative characterization of the rheological behavior of wheat flour dough during mixing. *Food Res. Int.* **2017**, *97*, 260–271. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Peighambardoust, S.H.; van der Goot, A.J.; van Zuilichem, D.J.; Boom, R.M. Application of shear in dough processing: Effect on rheology and gluten strength. *J. Cereal Sci.* **2005**, *42*, 61–68. [\[CrossRef\]](#)

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