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Study of Effect of Technological Parameters of a Continuous Mixer on the Quality of Wheat Flour Dough

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Abstract. The study aimed to determine the optimal dough mixing parameters to ensure the desired rheological properties. Experimental methods of dough mixing, rheological analysis and monitoring of process parameters were used, followed by comparison of the results with mathematical models to optimise the design of the processing bodies of the dough mixing machine. Design solutions that improve the stability of dough quality and increase production productivity were created in the study. The optimal design of the processing bodies of the dough mixer was established, which ensures the most efficient mixing of the components. The study demonstrated that different kneader designs and rotational speeds significantly affect the rheological properties of the dough, such as viscosity, yield strength, shear stress and shear modulus. The study determined that the use of an R/S rheometer provided accurate values of these parameters, while the optimal speed and design of the processing body reduced shear stress, ensuring uniform mixing. The study also determined that the temperature of the dough during kneading is critical for the activity of yeast and enzymes. The temperature parameters, which did not exceed 29°C, maintained yeast activity and ensured even fermentation of the dough. The optimisation of the kneading parameters improved the texture and taste characteristics of the bread, which confirms the high quality of the final products. The implementation of these results in production helps to increase the efficiency and stability of the process and can serve as a basis for improving dough-mixing machines. The practical significance of the study is determined by the possibility of using the obtained results to improve the quality of bakery products and optimise production processes by improving the design of dough mixers.

Keywords: rheological properties; temperature; ingredients; consistency; product quality; product volume

Дослідження впливу технологічних параметрів тістомісильної машини безперервної дії на якість тіста з пшеничного борошна

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Abstract. Дослідження було спрямоване на визначення оптимальних параметрів замішування тіста, щоб забезпечити бажані реологічні властивості. У цьому дослідженні були використані експериментальні методи замішування тіста, реологічний аналіз та моніторинг параметрів процесу з подальшим порівнянням результатів з математичними моделями для оптимізації конструкції робочих органів тістомісильної машини. У результаті дослідження були розроблені конструктивні рішення, що підвищують стабільність якості тіста і збільшують продуктивність виробництва. Встановлено оптимальну конструкцію робочих органів тістомісильної машини, яка забезпечує найбільш ефективне змішування компонентів. Дослідження показало, що різні конструкції місильних органів і швидкості обертання значно впливають на реологічні властивості тіста, такі як в’язкість, межа текучості, напруга зсуву і модуль зсуву. Було визначено, що застосування реометра R/S дозволило отримати точні значення цих параметрів, а оптимальна швидкість і конструкція робочого органу знижували напругу зсуву, забезпечуючи рівномірне замішування. Також виявлено, що контроль температури тіста під час замішування є критичним для активності дріжджів і ферментів. Температурні параметри, які не перевищували 29°C, сприяли збереженню активності дріжджів і рівномірному бродінню тіста. Досягнута оптимізація параметрів замішування дала можливість покращити текстуру і смакові характеристики хліба, що підтверджує високу якість кінцевих виробів. Впровадження цих результатів у виробництво сприяє підвищенню ефективності та стабільності процесу і може слугувати основою для вдосконалення тістомісильних машин. Практичне значення дослідження полягає у можливості використання отриманих результатів для підвищення якості хлібобулочних виробів та оптимізації виробничих процесів за рахунок удосконалення конструкції тістомісильних машин

Keywords: реологічні властивості; температура; інґредієнти; консистенція; якість продукту; об’єм продукту

Introduction

The production of bakery products is a complex process that requires precise control at every stage, especially when kneading dough. One of the key factors affecting the quality of the final product is the use of dough mixers, in particular continuous mixers. These devices ensure the stability of the kneading process and can significantly improve dough properties such as elasticity, consistency and homogeneity. However, to achieve optimal results, several process parameters need to be taken into account, such as kneading speed, temperature and intensity of mixing of ingredients. Consideration of these parameters provides a dough with the desired physical, chemical and rheological properties, which directly affects the quality of the finished product. Studying the technological parameters of kneading machines and their impact on dough properties is important for improving production processes and achieving high-quality standards in the bakery industry.

Z. Wang *et al.* (2021) determined that increasing the kneading speed improved the elasticity of the dough, but also caused overheating, which negatively affected the quality of the finished product. The authors also emphasised the importance of temperature control to avoid the destruction of the gluten structure. E. Mailybayeva *et al.* (2022) indicated that kneading temperatures above 25°C destroys gluten fibres, which worsens the quality of the dough and the volume of the finished product. The authors recommended keeping the temperature between 22-25°C to achieve optimal dough characteristics. Q. Zhao *et al.* (2024) proved that uniform dosing of ingredients ensured dough homogeneity and improved its physical and chemical properties. This avoided the formation of lumps and increased the stability of the final product. Z. Yaregal *et al.* (2022) argued that proper kneading improved yeast development, which affected the texture and taste of the finished product. The authors also highlighted the importance of controlling the kneading time to ensure uniform fermentation.

J. Xi *et al.* (2021) determined that optimal kneading parameters, such as speed and temperature, contributed to better dough porosity, which improved bread quality. The researchers proved that it also increased the flavour and freshness of the finished product. O. Parenti *et al.* (2021) noted that excessively long kneading times caused the dough to lose moisture, which worsened the texture. The researchers recommended adjusting the kneading time according to the characteristics of the flour and the type of product. E. Ntalios *et al.* (2024) emphasised that the use of continuous kneading on an industrial scale allowed for the stability and quality of the product to be maintained. The authors argued that precise control of technological parameters contributed to the uniformity of the quality of each batch of dough. X. Sun *et al.* (2023) emphasised the importance of moisture control during kneading, as it directly affected the elasticity and structure of the dough. The authors proved that the optimal moisture level improved dough properties and the final product. M. Venturi *et al.* (2022) studied the effect of different types of flour on kneading, finding that the composition of the flour determined the optimal machine parameters for achieving the best results. The researchers recommended adjusting the technological parameters depending on the quality of the flour to achieve consistent results. A. Gbabo *et al.* (2024) investigated the effect of kneading blade speed on dough homogeneity, finding that higher speeds contributed to a better distribution of ingredients. The researchers argued that this ensured dough homogeneity and improved its physical properties. However, research into this issue does not yet provide a complete answer to the question of optimal conditions for different types of flour and specific technological processes. For instance, the interaction between temperature and kneading time, as well as the impact of various ingredients such as additives and speciality flours on the final quality of the dough, needs to be further investigated. In addition, there is a need to develop more precise methods for controlling temperature and humidity during kneading to maximise product stability and quality in industrial environments.

The study aimed to demonstrate practical achievements in improving the design of a continuous-acting dough mixer, developing a rational kneading body and a method of controlling its operation.

Tasks of the study:

1. To analyse how changes in kneading speed, temperature and time affect the texture, elasticity and porosity of the dough.
2. To evaluate the relationship between the parameters of the kneading process and the quality of the final product.
3. To identify which factors are most critical to achieving optimal quality of bread and other products.

Materials and Methods

In this study, the influence of technological parameters on the dough-kneading process was analysed to determine the optimal design of the processing bodies of a continuous kneading machine. To achieve this goal, a variety of ingredients and innovative equipment were used, which was used to accurately determine the optimal conditions for the kneading process.

The ingredients for the dough were selected according to standard proportions used in baking (Soulaka & Morrison, 1985). The main ingredients were wheat flour, water – 42%, yeast – 2%, salt – 1.5% and sugar – 2%. The moisture content of the dough varied between 39% and 45%, which is the optimal range for a standard baking process. Thanks to the correct choice of ingredients, the required dough consistency was ensured, which allowed for further experiments.

The main equipment for the research was a continuous kneading machine manufactured by i2FOODS LLC (Ukraine). The machine was equipped with interchangeable processing elements, which were used to vary the design of the processing elements and study their effect on the dough-kneading process. The machine included a pre-kneading chamber and a final kneading chamber, which ensured efficient investigation of different configurations of the processing elements. The machine specifications included a capacity of 1,600 kg/h, a kneading time – of 200 to 300 seconds, and an electric drive power – of 5.4 kilowatts (kW) to achieve the required work intensity. Figure 1 shows a schematic diagram of a physical model of a continuous kneading machine consisting of a pre-kneading chamber and a final kneading chamber equipped with a new kneading body.

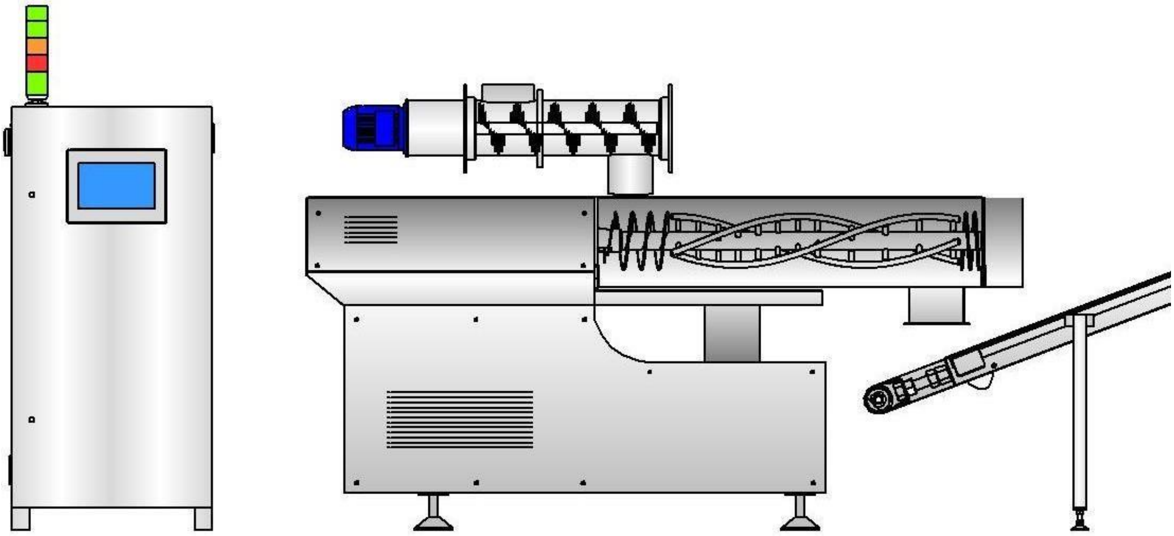

Figure 1. Diagram of the physical model of a continuous kneading machine
Source: *compiled by the author.*

To accurately analyse the rheological properties of the dough, the study used an R/S rheometer (Brookfield, USA) to measure important parameters such as viscosity, yield strength and shear stress, which are key to determining the structure of the dough and its ability to be further processed. This device provided accurate data, which was used to control and adjust parameters that affect the final properties of the product. To ensure stable conditions during the kneading process, a PC151MT-1-5M temperature sensor (PyroCouple Calex, UK) was used to continuously monitor temperature changes in the dough. This was important for maintaining the optimal temperature conditions necessary for yeast activity and achieving uniform fermentation. In addition, an ADS60G moisture meter (AXIS, Japan) was used to monitor the dough moisture content, which allowed for real-time moisture correction, ensuring optimal dough consistency for the best kneading results. A stationary SevenMulti pH meter (Mettler Toledo, Switzerland) was used to measure the pH of the dough and other components in the process. The use of these instruments in combination was used to achieve high accuracy of control over the process parameters, which significantly improved the quality of the final product. A batch-type kneader Diosna SP 240 AD (Germany) was used to efficiently knead various types of dough in the bakery and confectionery industry. Its design ensured the uniform mixing of ingredients and gluten development, which contributed to the achievement of optimal dough consistency and high-quality finished products.

Experimental studies included the creation and testing of various designs of processing bodies to identify the most efficient configuration that ensures an optimal kneading process. Different shapes and arrangements of the mixing elements were evaluated, as well as the impact of the kneading body speed on the quality of the kneaded dough. Continuous monitoring of parameters such as temperature, humidity and rheological properties allowed for prompt adjustments to the kneading conditions, which ensured that the desired dough characteristics were achieved, and the final product was of high quality.

Results

At the pre-mixing stage, wheat flour and liquid ingredients, according to the recipe of water – 42%, yeast – 2%, salt – 1.5% and sugar – 2%, were inserted into the pre-mixing chamber of the – premixer. In this chamber, the ingredients are mixed into a uniform mass, which ensures an initial even combination of dry and liquid components. This is an important step, as the correct mixing of ingredients at the initial stage contributes to the formation of a gluten network in gluten, which is the basis for the development of the dough structure. An important characteristic of a premixer is its ability to provide effective initial mixing, which is crucial for the further development of dough texture and quality. After the ingredients are mixed, a portion of the dough is transferred from the premixer to the final kneading chamber, where a more intensive process of creating the final dough structure begins.

In the final kneading chamber, the main kneading body of the kneading machine is installed. This kneading body rotates at a predetermined frequency, performing the necessary mechanical work to form the optimal dough structure. The mechanical load during the kneading process helps to achieve the desired dough texture and elasticity, which is critical for the subsequent production of high-quality bakery products. Controlling the temperature and speed of the kneading unit plays a special role in the kneading process, as it directly affects the efficiency of dough formation.

The innovative feature of the proposed dough mixer scheme is the division of the liquid phase into two separate streams: one goes to the premixer for the initial hydration of dry components, and the other – immediately to the main part of the dough mixing process, where the dough formation continues. This approach allows for more efficient process control and guarantees a consistent result, maintaining the same dough quality at all stages of its preparation. With this distribution of the liquid phase, the process of hydration and dough structure formation becomes more controlled, which is important for achieving the high quality of the final product.

To maintain optimum conditions during the kneading process, the dough temperature is regulated by the design of the kneading head. Adjusting the speed of the kneading body can create the desired intensity of mechanical processing of the dough, which is important for the stable development of its structure. Additionally, to avoid overheating of the dough during kneading, a cooling mechanism is used, which is carried out employing a double cooling jacket surrounding the kneading chamber. This cooling system maintains the optimum temperature and ensures the stability of the kneading process, which has a positive impact on the final quality of the dough and products.

The model of the kneading body of a kneading machine determines its shape, size, trajectory and rotation speed, which are critical parameters for high-quality dough (Figure 2). The characteristics of the kneading body, such as the angle of inclination, the number of revolutions and the geometry of the processing body, affect the uniformity of the distribution of ingredients, gluten development and dough aeration, which ultimately affects the structure, volume and texture of the finished product.

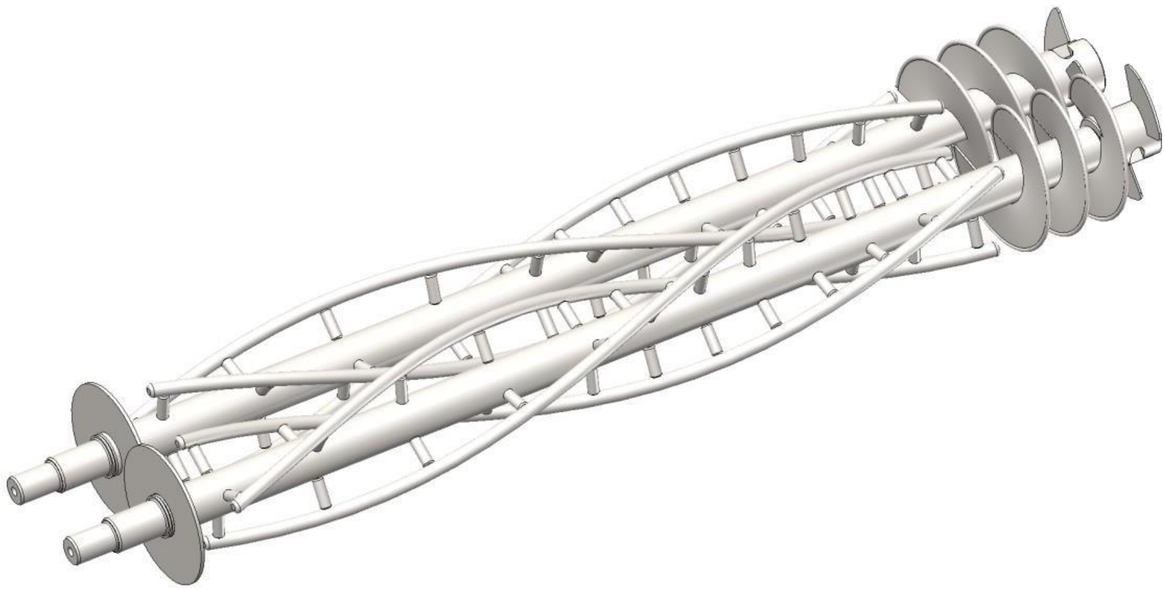

Figure 2. *Overview of the computer model of the kneading body of a continuous kneading machine*
Source: *compiled by the author.*

Figure 3 shows the process of kneading dough in the final kneading chamber, which is a key step in the dough production cycle. The chamber is equipped with a specialised kneading device that ensures intensive and uniform mixing of the dough. By performing rotational and axial movements, the kneading body creates optimal conditions for the development of the gluten backbone, even distribution of ingredients and the inclusion of a small amount of air in the mass. The design of the chamber contributes to the formation of a homogeneous dough consistency, which is critical to ensuring the high quality of the final product.

Figure 3. *Kneading the dough in the final kneading chamber*
Source: *compiled by the author.*

Figure 4 shows the drawings of the implemented kneading bodies. The study determined the optimal design parameters of the kneading body (shape, dimensions, rotational speed, structural reliability) and the final dough chamber (shape, dimensions, kneading time and temperature) to achieve the desired dough quality and rheological properties using four different kneading bodies. The following characteristics of the kneading machine were obtained during the tests: theoretical dough output – 1,600 kg/h, theoretical kneading time – 200-300 seconds, theoretical specific kneading work – 15 J/g, installed power of the electric drive of the kneading machine – 5.4 kW, kneading body speed control interval – 30-80 rpm.

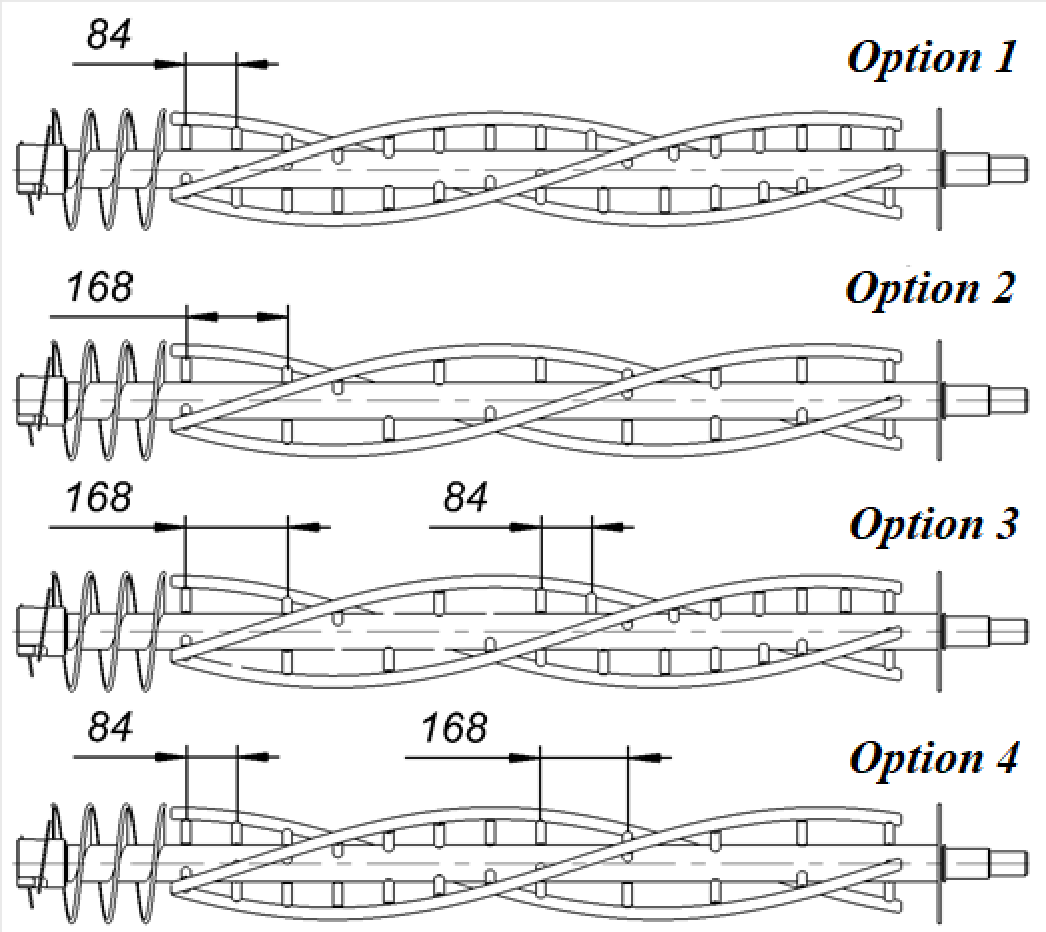

Figure 4. *Implemented variants of processing bodies*
Note: *Variant 1 Features a spacing of 84 millimetres (mm) between the spiral blade sections at the beginning of the shaft. Variant 2 Features a spacing of 168 mm between the spiral blade sections at the beginning of the shaft. Variant 3 Features an initial spacing between the spiral blade sections is 168 mm, with a further reduction to 84 mm. Variant 4 Features The initial distance between the spiral blade sections is 84 mm, with a further increase to 168 mm.*
Source: *compiled by the author.*

The study identified the main indicators of dough quality. Viscosity – a characteristic that determines the ability of a dough to resist deformation under the influence of an external force. Viscosity is a critical parameter in the kneading process, as it directly affects the efficiency of this process. The higher the viscosity, the more difficult it is to mix the dough components, which can lead to a deterioration in its structure and consistency. This is important to achieve the required homogeneity and texture of the final product, as well as to ensure stability during further processing steps such as fermentation and baking (Yang *et al.*, 2022).

Dough moisture (hydration) – determines the amount of water added to the flour during kneading to create a dough. The moisture content has an important influence on the texture and leavening of the product, as well as its elasticity. It affects the consistency of the dough by ensuring the right ratio of water to flour to form the necessary gluten network that gives the dough its elasticity. Excessive or insufficient moisture can lead to improper gluten development, which affects the quality of the finished product (Liu *et al.*, 2024).

Elasticity – the ability of the dough to regain its shape after the external load is removed. This parameter is important for maintaining the structure of the dough under mechanical stress. The elasticity of a dough is measured through the shear modulus (G'), which indicates its elasticity under shear deformation. High elasticity allows the dough to retain its shape after moulding and prevents it from tearing or deforming, which is important for good dough opening during baking (McCann & Day, 2013).

Dough temperature – an important factor in the activation of yeast and enzymes during kneading and fermentation. The right temperature ensures the optimum fermentation rate as well as the necessary conditions for the development of the gluten network, which has a significant impact on the texture and elasticity of the final product. Excessive or low temperatures can delay or accelerate these processes, which can compromise product quality (Sun *et al.*, 2023).

Acidity (pH) – acidity of the dough affects the activity of enzymes and yeast responsible for fermentation. The pH level also determines the chemical processes taking place in the dough, including the hydrolysis of starch and the activity of enzymes that break down proteins. The pH determines the stability of the dough structure and the quality of the final product. Too high or low an acidity level can affect the taste and reduce the efficiency of fermentation (Mohammadi *et al.*, 2022).

Dough strength – the ability of the dough to resist mechanical deformation during kneading and shaping. Dough strength is measured through two main parameters: shear stress and yield stress. Shear Stress shows how much force is needed to deform the material, while yield stress determines the minimum force at which the dough begins to flow or deform. These parameters are important for achieving the desired consistency of the dough and its ability to retain its shape during processing (Ojo *et al.*, 2023).

Shear modulus (G') – determines the stiffness or elasticity of the dough, which is important for assessing the texture and structural stability of the dough. The shear modulus helps to understand how the dough will react to mechanical stresses such as kneading and shaping. A high shear modulus indicates that the dough has a higher elasticity, which can provide better structural stability and prevent it from tearing or deforming during subsequent processing steps (Yazar & Demirkesen, 2023).

Shear Stress – the amount of force that acts per unit area parallel to the plane of a material. Shear Stress is an important parameter for determining the plasticity of a dough, as it determines how easily the dough can deform under external stress. This parameter helps to estimate how the dough will react to stress during mixing or other mechanical treatments (Seesala & Dhara, 2021).

Creep – the ability of a dough to deform over time under a constant load. Creep is an important parameter for determining the stability of the dough structure over time. This parameter is particularly important for assessing how a dough will behave during storage or long processes such as fermentation. Creep determines how the dough will change during these processes and whether its quality will be maintained (Sanz *et al.*, 2023).

Thixotropy – the ability of a dough to regain its viscosity after stress is removed. This parameter determines how quickly a dough regains its properties after the external stress is removed, which is particularly important in processes where the dough is subjected to stress changes, such as kneading or mixing. With high thixotropy, the dough quickly returns to its original viscosity, which contributes to the stability of the production process and ensures the quality of the final product (Torres-Gallo *et al.*, 2021). For the measurement of the parameters, the parameters are given in Table. 1.

Table 1. *Parameters that were defined in the study*

Device	Parameter to be measured
R/S rheometer from Brookfield	Viscosity; yield strength; shear stress; shear modulus (G'); thixotropy
Infrared temperature sensor PC151MT-1-5M (PyroCouple Calex)	Dough temperature
Moisture meter ADS60G (AXIS)	Hydration (humidity)
Stationary pH meter SevenMulti (Mettler Toledo)	Acidity

Source: *compiled by the author.*

Table 2 contains the reference parameters of the dough produced on the Diosna SP 240 AD batch kneader according to the specified recipe. It includes values that characterise the mechanical and physical properties of the dough, including its viscosity, yield strength, shear stress, shear modulus, temperature, hydration and acidity. These parameters are key to assessing the consistency and quality of the dough, which allows for process control and adjustments.

Table 2. *Reference dough parameters*

Viscosity, pascal-second (Pa-s)	220
Yield stress, pascal (Pa)	98
Shear stress, Pa	175
Shear modulus (G'), Pa	270
Temperature, °C	34
Hydration (humidity), %	39.6
Acidity, pH	4.8

Source: *compiled by the author.*

To determine the optimum kneading parameters, experiments were conducted that included a step-by-step change of kneading bodies. Each stage involved the measurement of various parameters, including the rheological properties of the dough, at different kneading body rotation speeds. During the experiments, different variants of kneading bodies were used, which were used to assess their effect on the characteristics of the dough. The results of the measurements for each kneading body were recorded and presented in Table 3-6, which shows the values of such parameters as viscosity, yield strength, shear stress, shear modulus and other important characteristics for each kneading body rotation speed. This data can be used to evaluate the effectiveness of different kneading bodies and their impact on the dough-mixing process.

Table 3. *Test results on the kneading organ Variant 1*

Parameter	Reference	40 RPM	45 RPM	50 RPM	55 RPM	60 RPM	65 RPM	70 RPM
Viscosity, Pa·s	220	247.8	231.4	212.7	201.1	192.2	182.3	168.7
Yield Stress, Pa	98	111.4	104.7	94.8	88.9	83.6	79.2	75.1
Shear Stress, Pa	175	188.6	182.3	168.9	156.3	147.4	140.9	132.8
Shear modulus (G'), Pa	270	289.4	275.9	258.7	246.1	236.8	225.1	217.2
Temperature, °C	31	27	28	28.5	29	29	31.5	34
Hydration (humidity), %	39.6	39.7	39.6	39.7	39.6	39.8	39.7	39.6
Acidity, pH	4.8	4.78	4.73	4.75	4.72	4.8	4.81	4.79

Source: *compiled by the author.*

As the kneading body speed increases, there is a decrease in viscosity, in particular from 247.8 Pa·s to 168.7 Pa·s, yield strength and shear stress, which indicates a decrease in resistance to dough movement. This indicates that the dough becomes more plastic and less resistant to deformation, allowing for a more efficient mixing of ingredients. The shear modulus also decreases, which confirms the decrease in the strength of the dough structure as the kneading body rotation speed increases. This effect may be the result of intensive mixing, which contributes to the breakage of some gluten and the loosening of the dough. The temperature of the dough rises at high speeds, which can affect the activity of enzymes and yeast, accelerating the fermentation process and changing the final texture of the product. However, the hydration and acidity parameters remain stable at all stages of the study, which indicates controlled kneading conditions and the preservation of optimal dough properties throughout the process.

Table 4. *Test results on the kneading organ Variant 2*

Parameter	Reference	40 RPM	45 RPM	50 RPM	55 RPM	60 RPM	65 RPM	70 RPM
Viscosity, Pa·s	220	258.1	240.6	219.8	210.3	199.6	190.8	178.9
Yield Stress, Pa	98	115.7	109.2	104.3	99.8	94.1	89.5	84.7
Shear stress, Pa	175	199.2	189.6	179.7	168.3	158.6	151.9	142.3

Shear modulus (G'), Pa	270	302.3	288.5	275.8	269.6	258.7	246.1	238.3
Temperature, °C	31	27	28	28.5	29	29	31.5	34
Hydration (humidity), %	39.6	39.7	39.6	39.7	39.8	39.5	39.6	39.8
	4.8	4.81	4.8	4.77	4.79	4.81	4.82	4.8

Source: *compiled by the author.*

With an increase in kneading speed, there is a decrease in viscosity, in particular from 258.1 Pa·s to 178.9 Pa·s, yield strength, shear stress and shear modulus, which indicates a decrease in dough stiffness. Therefore, with an increase in the speed of the kneading body, the dough becomes more elastic and less resistant to deformation, as the mobility of gluten molecules increases, making the dough softer and more plastic. A decrease in these parameters may also indicate that part of the dough structure is torn due to intensive mixing. The temperature during the kneading process also increases, which can affect the rate of fermentation, as a warm environment activates enzymes and yeast, accelerating the fermentation process. This can lead to changes in the texture and taste of the final product. At the same time, the hydration and acidity parameters remain stable at different rotational speeds, which indicates that these parameters are independent of the mixing intensity and are controlled at an optimal level throughout the process.

Table 5. *Test results on the kneading organ Variant 3*

Parameter	**Reference**	**40 RPM**	**45 RPM**	**50 RPM**	**55 RPM**	**60 RPM**	**65 RPM**	**70 RPM**
Viscosity, Pa·s	220	268.2	250.7	230.4	221.8	210.7	200.1	189.2
Yield Stress, Pa	98	120.5	114.9	109.6	106.4	101.8	95.6	90.2
Shear stress, Pa	175	208.1	197.8	188.2	181.3	172.6	158.7	151.3
	270	312.8	298.1	289.6	278.3	267.6	258.9	251.2
Temperature, °C	31	27	28	28.5	29	29	31.5	34
Hydration (humidity), %	39.6	39.6	39.7	39.6	39.8	39.6	39.7	39.6
	4.8	4.8	4.79	4.78	4.79	4.81	4.8	4.79

Source: *compiled by the author.*

Changes in parameters such as viscosity and shear stress show a decrease, specifically from 268.2 Pa·s to 189.2 Pa·s, with increasing kneading speed, indicating that the consistency of the dough improves at higher kneading speeds. Therefore, as the kneading speed increases, the dough becomes more plastic and less viscous, allowing for more efficient and even mixing of the ingredients. The reduction in shear stress also means that the dough becomes easier to move, which reduces energy consumption during processing. Changes in the shear modulus confirm a decrease in dough stiffness, as this parameter reflects the ability of the dough to resist deformation. At high kneading speeds, the dough structure becomes less rigid, which allows achieving the desired elasticity and homogeneity required for further processing and baking stages.

Table 6. *Test results on the kneading organ Variant 4*

Parameter	**Reference**	**40 RPM**	**45 RPM**	**50 RPM**	**55 RPM**	**60 RPM**	**65 RPM**	**70 RPM**
Viscosity, Pa·s	220	279.5	262.3	239.1	232.6	221.4	209.7	198.4
Yield Stress, Pa	98	126.2	119.6	113.7	109.4	106.3	99.8	93.6
Shear stress, Pa	175	218.4	207.3	198.6	187.4	177.5	169.6	159.7
Shear modulus (G'), Pa	270	319.7	308.9	298.4	288.2	278.9	268.4	258.7
Temperature, °C	31	27	28	28.5	29	29	31.5	34
Hydration (humidity), %	39.6	39.6	39.8	39.7	39.6	39.7	39.6	39.7
Acidity, pH	4.8	4.81	4.79	4.8	4.79	4.8	4.81	4.79

Source: *compiled by the author.*

All parameters show a downward trend with increasing kneading speed, which confirms the improvement of the elastic and flow properties of the dough. As the speed increases, the dough becomes more plastic and less viscous, which facilitates easier movement of the ingredients and more even mixing. The viscosity, yield strength and shear modulus parameters have the greatest decrease at high speeds, indicating greater mixing efficiency. This means that at high speeds, the kneading body has a more intense effect on the dough structure, breaking up its parts and relaxing the gluten, which improves the distribution of ingredients and facilitates dough processing in subsequent stages. Such changes indicate an optimisation of the kneading process, which leads to an improvement in the quality of the final product.

The plot obtained on the Brookfield R/S rheometer is shown in Figure 5.

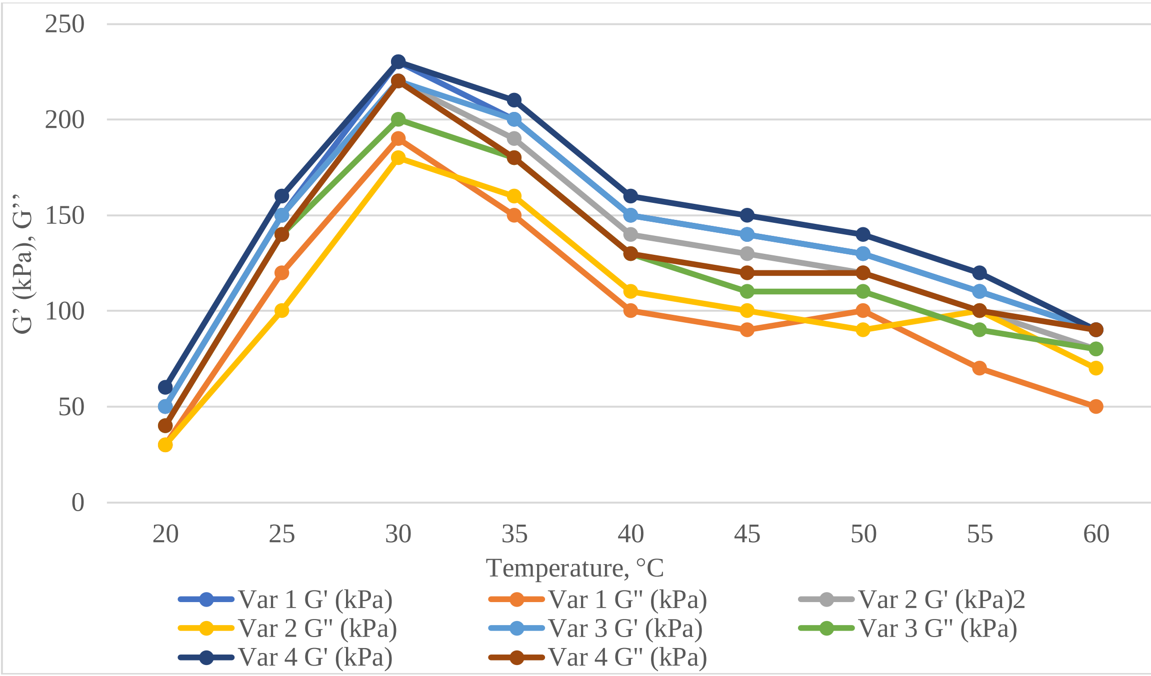

Figure 5. *Changes in the elastic modulus of dough with temperature*

Source: *compiled by the author.*

Based on the results of the plot, which reflects the ability of the material to change its shape under constant load, it is possible to conclude that Variant 4 demonstrates the best performance. This variant has the highest values of both the elastic modulus (G') and viscous modulus (G"), indicating its ability to retain structure and absorb energy during deformation. The high values of these parameters also indicate that the dough based on Variant 4 is more stable and resistant to external influences during mixing and further processing. In addition, this variant shows stability even when the temperature is increased, which is important to ensure a uniform kneading process. In addition, Variant 4 reaches peak values of elastic and viscous moduli at the optimal temperatures for yeast and enzyme activation, which vary from 28°C to 32°C. This ensures efficient dough fermentation, promoting the development of the gluten network and improving the structure of the final product. The dependence of the dough temperature on the speed was also investigated. The results are presented in the form of a graph in Figure 6.

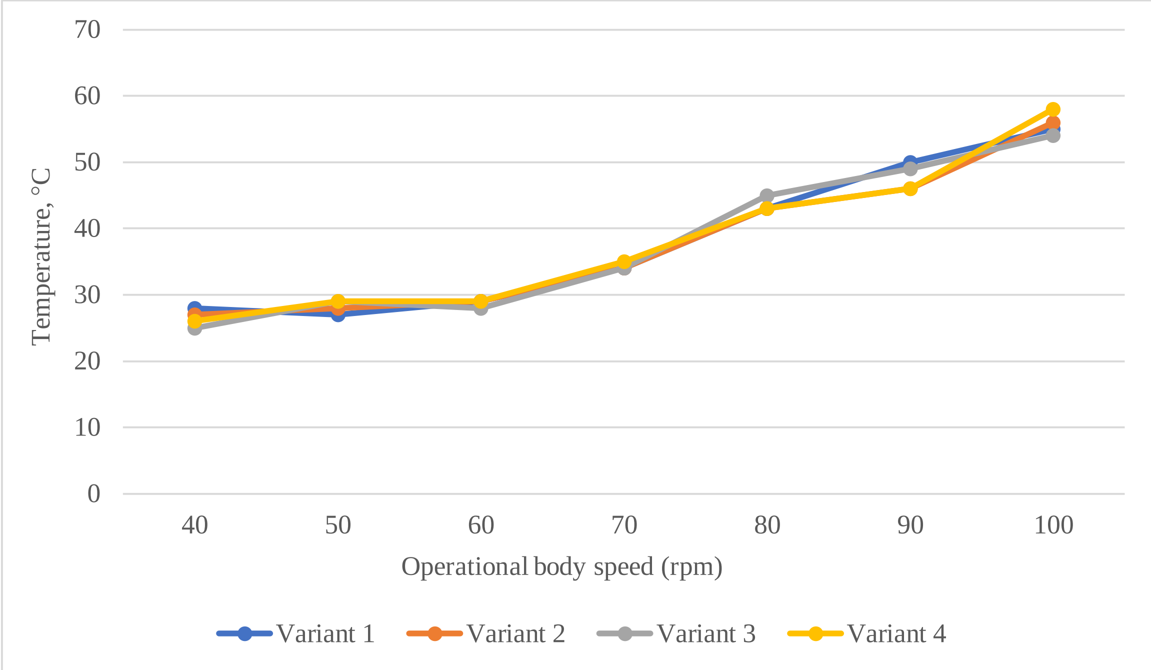

Figure 6. *Dependence of dough temperature on the speed of the operational body*
Source: *compiled by the author.*

The graph shows that the optimal speed of the processing body is in the range of 55-60 rpm. Increasing the speed increases the temperature of the dough. The main advantages of Variant 4 are essential for ensuring high dough quality and stability of the kneading process. High values of the elastic modulus (G') indicate the ability of the material to maintain its structural integrity and elasticity under load, which is important for a stable dough texture during kneading. It also contributes to the preservation of the gluten network, which determines the quality of the final product. High values of the viscous modulus (G") indicate the ability of the dough to absorb energy efficiently during deformation, reducing the risk of structural breakage during intensive kneading, which ensures the stability of the dough during the mixing process. Variant 4 also demonstrates stability with temperature changes, reaching peak values at 60-70°C, which is the optimal range for yeast and enzyme activation, promoting proper fermentation activity and gluten network development. Once the peak values are reached, the decrease in G' and G" indicates the stable behaviour of the material during temperature changes, ensuring a controlled kneading process and storage of optimal conditions for fermentation and dough structure.

Discussion

The study of the influence of technological parameters of a continuous kneading machine on the quality of wheat flour dough has resulted in important conclusions regarding the main factors that affect the physical and chemical properties of the dough. Changes in the rotational speed of the kneading bodies had a significant effect on such parameters as viscosity, yield strength, shear stress, shear modulus, temperature, hydration and acidity of the dough. The higher the rotational speed, the greater the decrease in viscosity and yield strength, indicating a decrease in the dough's resistance to deformation. This also indicates more efficient mixing and better homogenisation of the dough composition.

This problem was also investigated by S. Shrey *et al.* (2024), where the results confirmed that the study of the effect of the kneading body rotation speed on the mechanical characteristics of the dough shows that the speed directly affects the viscosity and elasticity of the final product. With an increase in the rotational speed of the kneading body, the energy transferred to the dough increases, which contributes to better mixing of the ingredients and the development of the gluten network. However, excessive acceleration can lead to excessive mechanical stress on the dough, which impairs its elasticity and contributes to the loss of the desired texture.

Q. Liu *et al.* (2024) demonstrated that the analysis of the effect of kneading temperature shows that temperature is important for the dough structure and fermentation process. High temperature can accelerate fermentation, which improves the dough rise rate, but it can also cause excessive heat and deterioration of the final product. The optimal temperature regime promotes even gluten development and efficient fermentation, ensuring a stable dough structure and high product quality.

Notably, the optimal kneading speed is a critical factor in achieving the desired mechanical properties of the dough, as it determines the uniformity of mixing and the development of the gluten network. Too high a speed can lead to excessive mechanical stress, which negatively affects the elasticity of the dough, while too low a speed does not ensure sufficient distribution of the ingredients. Therefore, it is necessary to find a balance that ensures the optimum viscosity and elasticity required for further processing and baking of the product.

The effect of hydration on dough structure was emphasised. The moisture content of the dough remained almost unchanged at different rotational speeds, which confirms that this characteristic depends more on the amount of water added to the flour than on the processing speed. However, it is worth noting that increasing the rotational speed of the kneading bodies reduced the mixing time, which could cause a slight decrease in the uniformity of hydration in the dough. At the same time, this did not have a significant impact on the quality of the final product, as the hydration remained within the optimal values for wheat flour.

J. Cheng *et al.* (2023) concluded that dough moisture is one of the most important factors that determines its texture and affects the quality of bakery products. The optimum moisture level can achieve the desired elasticity and softness of the dough, which ensures a uniform increase in volume during baking. Insufficient moisture can lead to a dry and hard texture, while excessive moisture can make it difficult to handle and lead to loss of shape during baking.

L. Wu *et al.* (2023) determined that dough pH is an important factor that directly affects fermentation processes, in particular yeast activity. An optimal pH level promotes better yeast growth, which ensures efficient fermentation and improved product quality. Too low or high an acidity level can slow down fermentation, which will affect the structure and taste of the finished product.

These results confirm the above study, as they demonstrate a correlation between the moisture level and the texture of the dough, which affects the quality of the finished product. The study determined that the optimum moisture content allows to achieve the desired elasticity and softness, which provides ideal conditions for the fermentation and moulding of the final product. In addition, the results confirm that incorrect moisture levels can negatively affect baking and product structure, which is consistent with the findings of previous studies on the importance of maintaining optimal dough parameters.

A decrease in viscosity and yield strength with increasing machine speed may indicate improved plasticity and easier kneading of the dough. At the same time, it may also be a consequence of changes in the structure of the gluten network, which is responsible for the elasticity of the dough. The results obtained indicate that at higher rotational speeds, the development of the gluten network is more intense, which affects the elasticity of the dough. This provides a better ability for the dough to restore its shape after deformation, which is an important factor in the production of bakery products.

It is worth highlighting the study by A. Cappelli *et al.* (2021), which also stated that the determination of optimal kneading conditions using high-speed kneading machines is important for improving the quality of bakery products. When using such machines, it is possible to achieve a more efficient distribution of ingredients and faster formation of the gluten network, which has a positive effect on the texture and elasticity of the dough. However, excessive speed can lead to overheating of the dough, which negatively affects its quality, so a balance between speed and temperature must be found.

M. Alongi & M. Anese (2021) concluded that the role of the kneading device in the kneading process is its ability to mix the ingredients evenly, ensuring the formation of a stable dough structure. A kneading device operating at the optimum load and speed promotes the formation of an elastic gluten network, which is critical to achieving the correct consistency. The correct kneading head setting can achieve maximum dough quality, ensuring that the dough has the optimum texture for further baking. This data confirms the importance of the correct setting of the kneading process parameters to achieve high-quality dough. In particular, the experimental results show that the optimal kneading speed and speed of high-speed machines are critical to ensure the even distribution of ingredients and the formation of the required dough structure. In addition, the combination of mechanical and biochemical methods mentioned in the previous section can indeed significantly improve the quality of the final product, while reducing the energy costs of the kneading process.

Regarding temperature, the study determined that with an increase in the rotational speed of the kneading organs, the dough temperature also increased. This confirms that more intensive mechanical processing increases the heat load on the dough, which can affect the activity of yeast and enzymes during fermentation. However, despite the increase in temperature, the acidity of the dough remained stable, indicating optimal conditions for fermentation and fermentation. This parameter also affects the quality of the final product, as the activity of enzymes that contribute to the leavening and development of flavour compounds depends on acidity.

A. Marzec *et al.* (2021) also conducted a study that confirmed that the speed of the kneading body is central to achieving the critical speed that ensures optimal dough quality. When this speed is reached, the dough acquires a uniform structure and elasticity necessary for further processing. At the same time, an excessive increase in speed can lead to overheating of the dough, which can affect its quality and texture.

A. Iztayev *et al.* (2023) also determined that intensifying the kneading process by combining mechanical and biochemical methods can accelerate the formation of the gluten structure and improve the structure of the dough. The use of enzymes and other bioactive additives helps to reduce the need for high rotational speeds, reducing energy consumption. This approach ensures process efficiency while improving the quality of the final product.

Comparing the data obtained during the research, it is possible to conclude that the optimal speed of the kneading body is critical for achieving high-quality dough. The experiments determined the limits of the critical speed, after which the elasticity and plasticity of the dough improved, which had a positive effect on further processing and baking. However, the study also determined that increasing the rotational speed beyond the optimum values can cause a decrease in dough quality due to overheating and excessive mechanical processing.

The pH analysis showed that its value was not significantly affected by changes in the speed of rotation of the kneading bodies. This indicates that the pH is consistently maintained within the optimum range, which ensures the proper activity of the enzymes responsible for the fermentation process. At the same time, pH values also correlate with the quality of the final product. The study showed that changes in acidity do not negatively affect the texture and taste of the dough.

Y. Gu *et al.* (2023) concluded that research into the effects of adding new ingredients to dough can expand the range of products and improve their nutritional properties. It is necessary to determine how these ingredients affect the mechanical properties of the dough, such as its elasticity, viscosity and stretching ability. This helps to adjust production processes to ensure consistent quality of the final product.

O. Ojo *et al.* (2023) determined that modelling and optimising the kneading process is important to reduce energy costs in production. The use of efficient kneading machines can reduce energy consumption while ensuring that the ingredients are mixed evenly. Optimisation of the equipment's operating parameters helps create a high-quality dough with predictable properties.

Analysis of study results determined that the addition of new ingredients significantly affects the texture and mechanical properties of the dough, including its elasticity and cohesion. Tests have shown that the optimal proportions of ingredients and kneading speed can ensure stable dough parameters, improving the quality of the final product. In addition, the modelling of the kneading process made it possible to assess the energy efficiency of dough mixers, which is an important aspect for reducing production costs and improving the economic efficiency of enterprises.

Thus, the technological parameters of a continuous kneading machine have a significant impact on the quality of wheat flour dough, in particular on its physicochemical properties, such as viscosity, elasticity, temperature, acidity and hydration. Increasing the rotational speed of the kneading bodies improves the mixing of the dough, which contributes to better gluten network development and elasticity, without a significant negative impact on acidity or hydration.

Conclusions

The study on the effect of the kneading body design and rotation speed on the rheological properties of the dough found that Variant 4 showed the best results in terms of dough quality. Variant 4 at 55 rpm showed the optimum viscosity value, which ensures the best dough structure. The viscosity value was 222 Pa-s, which corresponds to the average viscosity value for a high-quality dough. The increased viscosity helps to achieve a uniform consistency and proper elasticity of the dough, which is critical for the consistent quality of bakery products.

At a rotational speed of 55 rpm, the yield strength for Variant 4 was 110 Pa. This value indicates a high resistance to deformation of the dough, which ensures the preservation of its structure and volume during baking, contributing to the stability of the shape of the products during heat treatment.

The shear stress for Variant 4 at 55 rpm was 181 Pa, which is the optimum value for maintaining the elasticity and plasticity of the dough. This parameter ensures proper resistance of the dough to mechanical stress during kneading and moulding, which avoids structural damage.

Variant 4 at 55 rpm showed a shear modulus of 278 Pa, which indicates a high elasticity of the dough. A high shear modulus allows the dough to retain its shape during expansion and prevents it from tearing. This is important for achieving the desired texture and consistent quality of the final product.

The dough temperature for Variant 4 at 55 rpm did not exceed 29°C, which is important for maintaining the optimal activity of the yeast and enzymes required for dough fermentation. This ensures optimal conditions for fermentation, which has a positive effect on the quality of the products.

The automatic control system, using a programmable logic controller, ensures precise control and synchronisation of all process steps. The controller monitors process parameters and regulates the execution of technological operations. The diametric spectroscopy enables continuous control of the kneading body speed during the dough kneading process, depending on its consistency.

The limitation of the study is the use of only one type of wheat flour and the lack of consideration of variable factors such as ambient temperature and humidity. For further development of the study, it is necessary to study the effect of different types of flour and their moisture content on the rheological properties of the dough when using different kneading body rotation speeds.

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None.

Conflict of Interest

None.

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