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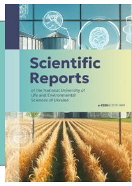

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Automated OptiMix-360 system for continuous dough mixing: Technical solutions and efficiency

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Abstract. Enhancing the efficiency and stability of industrial dough production is achievable through the implementation of innovative technologies that optimise quality and reduce costs. The objective of this study was to evaluate the efficiency of the OptiMix-360 system for industrial dough production by integrating technologies such as gravimetric dosing, premixers, and dough mixers and to determine its impact on improving productivity and final product quality. The research methodology was based on an experimental approach that assessed the efficiency of the OptiMix-360 system compared to traditional methods by measuring product quality parameters and process performance under different operating conditions. The study analysed the effectiveness of the GraviFlow Master, TORNADO-2, and ProMix D-Helix equipment based on performance indicators, energy consumption, dosing accuracy, and final product quality when these technologies were integrated into the production process. The implementation of the OptiMix-360 system resulted in a significant productivity increase to 1500 kg/h, a 30% reduction in energy consumption, and consistent dough batch quality. The gravimetric dosing system ensured an accuracy of <0.1%, enhancing composition stability, while the TORNADO-2 premixer improved flour hydration and gluten formation, positively affecting the texture and strength of the final product. The production process was stabilised, and product quality fluctuations were minimised due to automation and adaptive settings. The obtained results confirmed the effectiveness of the OptiMix-360 system in industrial practice. This technology not only improved dough quality but also reduced energy consumption costs and increased productivity. The application of the OptiMix-360 system in the food industry holds high potential for improving production efficiency, reducing energy costs, and ensuring consistent product quality

Keywords: food industry; rheology; fibrin; gluten; bakery industry

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Introduction

The development of the food industry, especially the bakery industry, largely depends on the introduction of innovative technologies, since the market places high demands on the quality, stability, and variety of products. In this context, there is a need to optimise technological processes, in particular in the production of dough, which is the main component of bakery products. The growing scale of production and the requirements for its efficiency increase the relevance of integrating automated mixing systems.

Conventional methods of periodic kneading of dough used in many enterprises have a number of disadvantages. The main ones are the heterogeneity of the final texture, high energy intensity, and a significant influence of the human factor on production processes. These problems were analysed by O.I. Petrova & N.P. Shevchuk (2020), who pointed out the importance of implementing automated solutions to improve the quality of dough and reduce losses. M. Sanitska (2023) noted the need to adapt the mixing systems used to the requirements of medium and large enterprises to improve production efficiency. However, many issues remain unresolved, in particular, the integration of continuous kneading processes and their automation.

Automation of technological processes in the bakery industry was considered as an important area of industry development. A.A. Solianyk (2021) studied in detail the impact of automated lines on the production of sponge products, emphasising their ability to increase productivity and reduce energy consumption. However, the main focus of his research was on confectionery products, while kneading dough for bakery products requires a specific approach, considering the variety of recipes and processing parameters.

M. Obadi *et al.* (2022) also focused on improving kneading technologies, especially in the production of noodles. Studies have shown that the integration of new technologies, such as the use of premixes and automated dough mixers, significantly improves the quality of the final product. However, questions about the economic feasibility of implementing such systems for bakery products remain poorly understood. Similar accents were indicated in the study by A. Singh (2021), where the researcher reviewed the evolution of technology in the bakery industry. The author noted the importance of switching to automated continuous processes, but most of the analysis concerned general aspects of automation, without a detailed analysis of the specifics of kneading dough.

Research in the field of dough kneading indicates the need to improve technologies. In particular, G. Campbell & P. Martin (2020) emphasised the importance of aeration of the dough during kneading, as it directly affects the rheological properties and the level of rise of the dough during baking. The researchers also focused on the critical role of the interaction of ingredients and technological parameters in the aeration and dough structure.

Y.-L. Yang *et al.* (2021) conducted a study that focused on the effect of vacuum degree, mixing rate, and water quantity on moisture distribution and rheological properties of wheat flour dough. The results provided new opportunities for optimising technological parameters in the processing of flour dough. As noted by A. Cappelli *et al.* (2020), kneading is one of the key stages of bakery production, affecting not only the structure of the dough, but also the final organoleptic properties of bread. The researchers systematised approaches to improving the rheology of the dough by adjusting the intensity of mechanical impact, and integrating new ingredients that improve the structural characteristics of the dough. However, their research focused mainly on laboratory conditions and did little to highlight the adaptation of these methods for large-scale industrial production.

S. Tietze *et al.* (2019) made a significant contribution to understanding the effect of mechanical shear on the development of the gluten mesh. They focused on the relationship between the intensity of kneading and the quality of dough, especially in the production of wheat bread. However, their research pointed to the problems of overheating of the dough and uneven influence of mechanical energy when using conventional kneading systems. These aspects highlight the need to improve existing technologies to minimise the shortcomings of traditional approaches. R. Jerome *et al*. (2019) in their review paper examined the role of analytical control technologies in the bakery industry, noting their importance for optimising technological processes. The researchers noted that the introduction of process-analytical technologies can increase the level of production automation, reduce the influence of the human factor, and ensure the stability of product quality. However, the specific analysis of continuous mixing systems remains poorly covered in their research, which has created gaps in understanding the benefits of such systems for industrial scale.

The purpose of this study was to create and analyse the effectiveness of the OptiMix-360 automated continuous dough kneading system, capable of working with various types of flour.

Materials and Methods

The study was conducted using the integrated technological system OptiMix-360, specially adapted for the production conditions of food industry enterprises. The technological scheme of the equipment is shown in Figure 1.

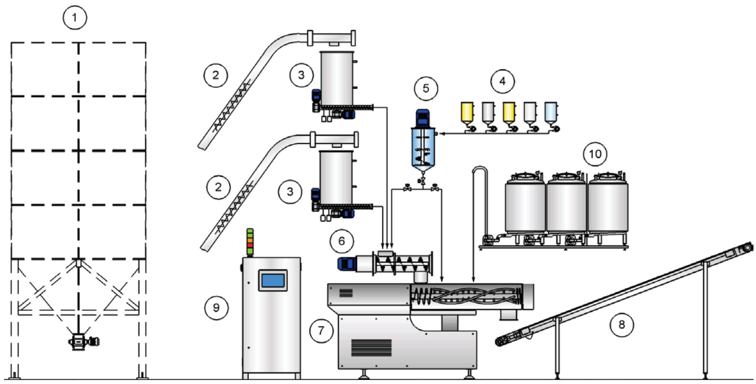

Figure 1. *Machine and hardware diagram of the OptiMix-360 system*

Note: 1 – flour storage silo (Golfetto Sangati, Italy); 2 – flexible screw feeder for flour transportation (Flexicon, USA); 3 – gravimetric dosing system GraviFlow Master (Chronos Richardson, Great Britain); 4 – microdosing unit for liquid components (Dosatron D30WL2, France); 5 – turbomixer for pre-solution (Ika Ultra-Turrax, Germany); 6 – premixer TORNADO-2 (Tetra Pak, Sweden); 7 – continuous dough mixer Promix D-Helix (WP Kemper, Germany); 8 – conveyor for dough maturation (Intralox, USA); 9 – control unit with programmable logic controller (Siemens S7 – 1500, Germany); 10 – CIP system for automatic washing (Alfa Laval, Sweden)

Source: compiled by the author

At the first stage of the study, precise microdosing of liquid components was performed using a specialised Dosatron D30WL2 unit (France). The components were pre-weighed on a high-precision laboratory scale Mettler Toledo (Switzerland). The dosage error did not exceed 0.1% of the total weight of the components. The unit provided automated injection of liquids in appropriate proportions, which helped to avoid the influence of the human factor and ensured the stability of the process. Mixing of liquid components with water was carried out in a turbomixer (Ika Ultra-Turrax, Germany) for the solution, which ensured uniform distribution of the liquid and the formation of a homogeneous liquid phase for subsequent introduction into dry ingredients. The resulting liquid ingredients were mixed with water until a homogeneous liquid phase was formed. At this stage, a turbomixer (Ika Ultra-Turrax, Germany) was used, which ensured complete homogenisation of the mixture before its subsequent integration with dry components.

The GraviFlow Master System (UK) provided continuous gravimetric dosing of three types of flour, depending on the requirements of the recipe. Using load cells, the accuracy of flour weight measurements was ±0.05%, which guaranteed the stability of the resulting dough. The liquid phase was gradually added to the dry components in the TORNADO-2 premixer (Sweden), which provided the initial combination of ingredients. A special feature of this stage was the active development of a gluten mesh, which is necessary for the correct structure of the dough.

At the main kneading stage, the ProMix D-Helix dough mixer (Germany) was used, which provided a soft but energy-efficient introduction of mechanical energy into the dough. The process took place in two stages: one stream of the liquid phase was fed to the premixer, the other – directly to the dough mixer. The system worked with maintaining a stable temperature of 28-30°C using a double jacket, which provided optimal conditions for the development of the dough structure.

Automation of the OptiMix-360 system was carried out using a programmable logic controller Siemens S7-1500 (Germany), which performed monitoring and adaptive control functions at all stages of the technological process. Built-in sensors tracked key parameters such as humidity, temperature, ingredient proportions, and component flow rate. Data from the sensors was processed in real time, which allowed automatically adjusting the equipment settings. The Human-Machine Interface (HMI) provided intuitive process control for the operator, visualising key parameters and system status. The remote monitoring function based on the Internet of Things technology helped to perform diagnostics and quickly respond to any deviations, reducing equipment downtime.

The effectiveness of the study was evaluated by indicators of stability of the consistency of the finished dough (40-45% moisture, depending on the recipe); process productivity (1,200 kg/h) and minimisation of material losses (dosage deviation <0.1%). All measurements were carried out under laboratory and semi-industrial conditions, which allowed adapting the results for practical application.

The study also evaluated the conventional system of periodic kneading of dough Diosna W240A (Germany), which involves the use of large bins or bowls. This system is characterised by a number of disadvantages: limited flexibility, since each batch of dough requires individual settings; heterogeneity of quality due to uneven mixing; high energy intensity caused by significant mechanical losses; and labour intensity of maintenance. In contrast, the OptiMix-360 provides a continuous, energy-efficient and fully automated process, reducing the impact of the human factor and improving quality and productivity.

During the implementation study of the OptiMix-360 technology system, a number of ISO standards were observed that ensure high quality, safety, and efficiency of processes. In particular, the ISO 9001:2015 (2015) standard was used for quality management systems, which ensures compliance with all requirements at every stage of the production process. It also considered the requirements of ISO 22000:2018 (2018) for the food safety management systems, which is important for the production of food components, and ISO 45001:2018 (2018) for occupational safety, which reduces risks to personnel, especially when working with high-tech systems. These standards have become the basis for ensuring the stability and safety of the studied processes in industrial conditions.

Results

Characteristics of the main technological components of the OptiMix-360 system. The GraviFlow Master gravimetric dosing system is an innovation in the field of bulk material dosing and belongs to the category of continuous weighing systems (Fig. 2). It provides a precise and stable flow of components, which is critical for industrial processes such as dough kneading. The main principle of operation of the system is to continuously measure the weight of material in the hopper using load cells that transmit data to the controller. The controller analyses this data and automatically adjusts the feed rate, ensuring the stability of the material flow in accordance with the specified parameters. The hopper used for storing bulk materials is designed to ensure their smooth and uniform flow. High-precision load cells constantly measure the weight of the material in the hopper, which is the basis for the operation of the system. A screw conveyor or vibrating feeder is often used as a feeding device, which provides a controlled flow of materials. The controller integrates all sensor data, analyses it in real time, and adjusts the feed rate if deviations are detected to ensure that the actual material flow matches the desired one.

Figure 2. *GraviFlow Master gravimetric dosing system*

Note: the system consists of the following key elements: a hopper for storing bulk materials (provides storage of the metered component, optimising its feed); load cells (located on the hopper, they continuously measure the weight of the material in real time); a controller (processes data from load cells and, depending on the information received, adjusts the feed rate of the material); a feed device (screw conveyor or vibrating feeder), which provides a controlled flow of material based on the received signals from the controller

Source: compiled by the author

The system control loop is based on the feedback principle. When the desired feed rate is set, the system continuously compares it with the actual speed obtained from the load cell readings. The controller processes this data, and if it detects discrepancies, it instantly corrects the operation of the feed devices. This ensures that a stable material feed rate is maintained even under variable production conditions.

GraviFlow Master has a number of important advantages. The accuracy of the system allows minimising dosing errors to less than 0.1%, which is critical for the stability of the dough characteristics. Consistency and uniformity of dosage ensure uniformity of the composition and quality of the product. The effectiveness of this technology is also manifested in saving materials and reducing the amount of waste, which increases the economic feasibility of its use. The flexibility of GraviFlow Master allows adapting it to work with different types of materials and requirements of production processes. When implementing continuous weighing system, certain difficulties may arise, in particular, inhomogeneities in the flow of materials due to vibrations or pressure fluctuations, which can affect the accuracy of measurements. To solve such problems, methods of vibration isolation, advanced control of motors of feed devices and compensation of pressure fluctuations are used. GraviFlow Master has proven its efficiency and adaptability in dynamic industrial environments. Its integration into production lines such as the OptiMix-360 system has ensured accurate dosing, process stability, and improved the quality of the finished dough.

Another important step in the production of dough is pre-mixing, as it significantly affects the characteristics and quality of the final product. This process begins with a combination of ingredients such as flour and water, which leads to the formation of gluten – the structure that ensures the strength and elasticity of the dough (Sattarov *et al.*, 2024). It is pre-mixing that creates the necessary conditions for the activation of flour proteins, gliadin and glutenin, and an even distribution of moisture.

The TORNADO-2 premixer has demonstrated significant advantages in this process due to its innovative design. The device provides a fast and efficient combination of ingredients with minimal loss of mechanical energy, which avoids the development of lumps and preserves the integrity of the dough structure. Chemical and physical interactions in the dough that occur during pre-mixing play an important role in its structure and texture. The process of protein hydration is the first step: proteins absorb water and interact with each other, forming a three-dimensional gluten structure. Gliadin is responsible for the stretchability of the dough, and gluten gives it strength. In addition, starch hydration contributes to the creation of a homogeneous mass, acting as a filler and connector between proteins. The mechanical energy transferred during the mixing process helps to stretch and align protein molecules, strengthening the structure of gluten. However, excessive exposure to mechanical energy can disrupt the structure of the dough, so precise control of the process is an important factor. Temperature plays an equally important role: optimal protein hydration conditions are provided in the range of 26-36°C.

TORNADO-2 allows optimising all aspects of pre-mixing. It is designed to maintain a stable temperature regime, and the use of advanced mechanical elements minimises possible disadvantages, such as overheating or structural damage. The result is a high-quality dough with an even distribution of moisture, a stable texture and a strong gluten mesh. Pre-mixing in TORNADO-2 provided an efficient start to the dough forming process, creating optimal conditions for subsequent stages such as kneading and maturation. This device has proven its effectiveness in improving the consistency of dough, which is the key to high quality bakery and pasta products. Due to the introduction of this technology, it was possible to achieve stable quality of the final product and reduce the number of defects in the production process. The ProMix D-Helix dough mixer is a solution in continuous dough kneading technology that offers numerous advantages over conventional periodic kneading methods. Its design ensures high efficiency, compactness and reliability, making this machine an ideal choice for industrial production (Fig. 3).

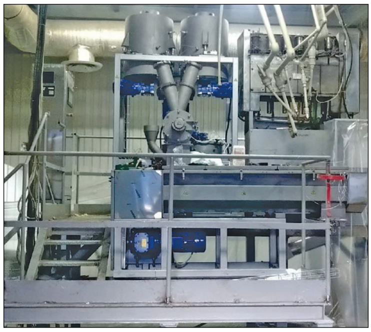

Figure 3. *ProMix D-Helix dough mixer*
Source: compiled by the author

One of the main advantages of ProMix D-Helix is the use of an innovative bowl with a circulation cooling system, which allows precisely controlling the temperature regime throughout the entire process. This is necessary to maintain the optimal texture of the dough and prevent it from overheating. A special feature of the dough mixer is the unique kneading organs made in a combination of two shapes (Fig. 4). One part is shaped like an auger, which allows for directional movement of the dough, while the second, similar to the "DNA molecule", promotes delicate mixing without excessive shear or cutting, which can negatively affect the quality of the dough structure.

Figure 4. *Kneading part of the ProMix D-Helix dough mixer*
Source: compiled by the author

ProMix D-Helix uses the principle of careful use of mechanical energy. The energy distribution during kneading aligns and stretches gluten molecules, contributing to the development of a stable and elastic gluten mesh. This process ensures the correct development of the dough structure, making it elastic and able to maintain its shape during baking. It is important to note that controlling the kneading intensity avoids excessive mechanical impact, which can disrupt the gluten mesh, turning the dough into an excessively elastic and dense mass.

Special attention is paid to the effect of friction during kneading, since the release of heat can increase the temperature of the dough. ProMix D-Helix, due to its cooling system, provides a stable temperature, which prevents protein denaturation and weakening of the gluten mesh. The result of this control is high quality dough with a strong texture and optimal properties for further production. The flexibility of the ProMix D-Helix design allows adapting the kneading organs for different types of dough, such as lingering cookies or rye bread. The versatility of this technology makes it easy to replace components for working with various formulations, which is an additional advantage for large-scale industrial processes. Thus, the use of ProMix D-Helix significantly improves all key indicators of dough kneading, including its texture, stability and adaptability to various production conditions.

The results of the implementation of the OptiMix-360 system for continuous kneading of dough in industrial conditions demonstrate significant advantages over conventional methods of periodic kneading. The study provides key metrics obtained during system testing, including dough quality, energy saving, production capacity, production flexibility, and ease of operation and maintenance.

Dough quality. The OptiMix-360 system provides excellent consistency stability for each batch of dough due to precise compliance with technological parameters and uniform processing conditions. Thanks to the integration of advanced gravimetric dosing systems and automatic mixing control, the gluten mesh was formed evenly, which guaranteed high elasticity of the dough. The mechanical action of the ProMix D-Helix system, combined with controlled hydration, helped to avoid structural breaks, which is often observed in conventional systems. The stable consistency reduced baking variations, which is an important factor for large-scale production. This allowed increasing the predictability and quality of the finished product, minimising production waste due to defects in the structure or consistency of the dough.

Due to the precise observance of temperature and humidity parameters throughout the entire process, the OptiMix-360 system has created a dough with a perfect texture. Smoothness and uniformity of the surface were achieved by step-by-step introduction of liquid components through the TORNADO-2 premixer and efficient mixing in ProMix D-Helix. It is important to note that the structure of the dough eliminated the problem of tearing off the top of the bread, which was characteristic when using conventional kneading methods.

This characteristic significantly improved the final quality of baked goods, preserving their shape and texture properties. Combined with the ability to work with different types of flour (rye, wheat, mixed recipes), OptiMix-360 demonstrates advantages in the production of a wide range of bread.

Compared to conventional batch kneading systems such as Diosna W240A or Kemper SP150, the OptiMix-360 system provides significantly better dough texture uniformity due to its continuous processing process. The absence of the need for unloading and re-dosing reduced the risk of local changes in the mixing of components, which positively affected the overall quality. Due to this, the final baked goods were characterised by stable dimensions, smooth surface, and more pronounced organoleptic properties. The high quality of the dough texture also contributed to better moisture retention in baked goods, increasing their freshness period.

During the testing process, it was found that the dough processed by the OptiMix-360 system has optimal strength and tensile ability, which are key indicators of high-quality bakery products. The elasticity of the dough helped to significantly reduce breaks when forming products and cutting ready-made bread.

Productivity and energy efficiency of the process. The OptiMix-360 system demonstrated high productivity, reaching a production capacity of up to 1,500 kg/h, which exceeds the originally planned figure of 1,200 kg/h. This result is made possible by integrating a continuous flow of technological processes, which eliminates the need to stop between mixing stages. This significantly reduces the time spent on preparatory operations. The key is full automation, which reduces the risk of human exposure. Programmable logic controllers, together with sensors that monitor all the main parameters (humidity, temperature, component feed rate), helped to maintain ideal conditions for the process, which guarantees the stability and uniformity of each batch of dough. Thus, production operated continuously, which significantly increases the volume of products without loss of quality.

The OptiMix-360 system reduces power consumption by 30% compared to conventional periodic mixing systems. This savings were achieved by reducing the mechanical load on the dough due to the uniform distribution of energy during mixing. Additionally, automated process control ensures precise temperature control using a double jacket, which eliminates overheating of the dough and irrational energy consumption. A key role in achieving energy efficiency was played by sensors that provided constant monitoring of process parameters and timely adjustment of equipment operation. The integration of such components helped to optimise energy consumption at all stages of kneading.

Flexibility, adaptability and ease of use. The OptiMix-360 system has demonstrated the ability to work effectively with a variety of dough recipes, including rye, wheat, and rye-wheat. This flexibility allowed adapting the production process to various technological requirements that arose due to changes in the characteristics of raw materials or consumer requests. The system provided the ability to quickly adjust parameters in real time due to the integration of sensors and control algorithms. Making changes to the formulation did not affect the quality of the final product due to precise control over all parameters – from temperature to the proportions of components. Adaptability ensured the stability of the process and helped to avoid losses of raw materials even in conditions of variable dough composition.

The OptiMix-360 made it easy to operate with an intuitive HMI that allowed operators to access visualised system status data. The controllers monitored key parameters, and any deviations from the set indicators were immediately displayed on the operators' screens. This made it easier to make decisions and faster to respond to potential problems. The remote monitoring function based on the Internet of Things helped to quickly diagnose and fix problems, minimising equipment downtime. The simplicity of the system's design also played an important role: the components were positioned in such a way as to provide easy access for maintenance and cleaning. This reduced the time and effort required to prepare the equipment for further operation, which further increased overall efficiency.

Thus, the implementation of the OptiMix-360 system allowed achieving stable dough quality, increasing production efficiency, and reducing operating costs (Table 1). The results obtained indicate its suitability for large-scale implementation in industrial bakery enterprises.

The results obtained during the study of the OptiMix-360 system indicate significant advantages of this technology in the industrial production of dough. All key aspects – from dough consistency to energy efficiency – showed a significant improvement over conventional batch kneading methods. Due to precise control at every stage, starting with microdosing of components and ending with final kneading, it was possible to achieve a stable consistency and uniformity of gluten mesh formation. This result directly affected the improvement of the dough texture, which became the basis for the production of high-quality baked goods.

Table 1. *OptiMix-360 system performance compared to the conventional method*

Indicator (%)	Conventional method	OptiMix-360 system
Quality	70	95
Energy saving	50	80
Production capacity	100	125
Production flexibility	65	85
Easier operation and maintenance	55	75

Source: compiled by the author

The energy efficiency of the system is another significant achievement. The recorded reduction in energy consumption by 30% compared to conventional systems was made possible by the use of upgraded process control mechanisms and minimising the mechanical load on the dough. This not only reduced operating costs, but also helped to optimise production processes, making the system more environmentally friendly. The OptiMix-360's performance, which has reached 1,500 kg/h, is proof of its technical improvement. The ability to maintain high productivity without compromising product quality has significantly increased production volumes, which is especially important for large industrial enterprises.

Advantages and limitations of the system. The introduction of the OptiMix-360 system in production has led to several strategic advantages. In particular, due to the continuity of the mixing process and full automation, it was possible to eliminate downtime characteristic of periodic systems and achieve a reduction in overall energy, repair, and maintenance costs. In addition, the uniformity and stability of the dough parameters were ensured by final products with improved texture, structure, and taste qualities. This not only meets consumer expectations, but also meets high market standards.

In addition, the system allowed adapting to different types of flour, recipes, and quickly changing production parameters without stopping the technological process. This has expanded the product range, allowing products to be produced for various consumer segments, including organic and speciality products. Intuitive HMI, process automation, and easy maintenance reduced the need for a large number of maintenance personnel and reduced downtime.

Along with the advantages, the study also revealed certain limitations of the OptiMix-360 system. The first and most significant is the high cost of implementation. The initial cost of purchasing and installing the system can be significant for small and medium-sized enterprises, which can become a barrier to its mass implementation. In addition, high automation requires a qualified approach. To maximise the use of the system's capabilities, training of operators and technical personnel is required. An important aspect of successful operation is the dependence on the accuracy of settings, since for optimal operation it is necessary to configure the system for specific production conditions, and errors at this stage can lead to a decrease in productivity or product quality. The influence of external factors, such as vibrations or pressure fluctuations in the production environment, can affect the accuracy of dosing or settings, which requires additional stabilisation solutions. The results of the implementation of the OptiMix-360 system show that it is a promising tool for optimising production processes, in particular in the bakery industry. Consideration of limitations and potential risks will avoid difficulties and ensure its maximum effectiveness in the long term.

All stages of production met the requirements of ISO 9001:2015 (2015) for quality management systems, which ensured compliance with all critical requirements. The ISO 22000:2018 (2018) standard for the food safety management systems confirmed proper risk management in food production, and ISO 45001:2018 (2018) contributed to minimising production risks and improving occupational safety, especially in the use of technologies with high requirements for accuracy and efficiency, such as the OptiMix 360 system. Due to compliance with these standards, the stability and safety of technological processes at all stages is achieved.

Discussion

The results of the study confirm that the integration of the OptiMix-360 system has significantly improved the quality of dough, increased the efficiency of production processes, and reduced energy costs. In particular, the study confirmed a significant impact of process structure and control on dough quality, which is consistent with the results published by A. Ktenioudaki *et al*. (2010). The researchers investigated the effect of various kneading processes on the rheological characteristics of the dough, finding that the uniformity of mechanical energy supply and effective hydration are crucial for obtaining a uniform texture. The OptiMix-360 system, due to the TORNADO-2 premixer and the ProMix D-Helix dough mixer, ensured proper hydration and energy distribution, which helped to achieve a high-quality gluten mesh. One of the key areas of modern development of production systems is the introduction of artificial intelligence and automated control algorithms, which was confirmed by E. Carpanzano & D. Knüttel (2022). Their findings show that the use of intelligent systems in production processes can significantly improve stability and productivity. The OptiMix-360 system implements similar approaches – automated process control is carried out using programmable logic controllers (Siemens S7-1500), which allows quickly adapting the process parameters.

The study by V. Piddubnyi *et al.* (2024) showed that proper design of kneading processes helps to improve the quality of the final product and reduce energy consumption. Optimisation of the kneading process through automatic gravimetric dosing and pre-mixing, which is used in OptiMix-360, confirmed these results, in particular, in reducing energy consumption by 30%. S. Dhal *et al*. (2023) analysed the effect of mixing time on the properties of whole-grain flour cookie dough. It was found that the optimal mixing time helps to achieve the necessary uniformity and texture of the dough, which also confirms the importance of mixing control in this study. The study used innovative approaches, in particular, gravimetric dosing and adaptive mixers, which automate and more precisely regulate the mixing process for stable dough quality.

Z. Muchová & B. Žitný (2010) emphasised the importance of improving approaches to dough mixing, considering various external factors, such as vibrations. The OptiMix-360 system takes these aspects into account, as it has design solutions to minimise the impact of vibrations on dosing accuracy and process stability. C. Rosell & C. Collar (2009) focused on the effect of temperature and consistency on dough performance. In particular, they investigated how different temperature conditions affect the formation of gluten mesh and the strength of the dough. The ProMix D-Helix circulation cooling system prevents the dough from overheating during kneading, which ensures proper structure development. This is consistent with the authors' conclusions, which emphasise the need for strict control of temperature conditions to achieve stability of dough quality. The use of a circulating cooling system in ProMix D-Helix reduced the risk of overheating of the dough, which is consistent with the recommendations of F. Aghili (2021) on mechanical load management in production processes. The OptiMix-360 system uses adaptive algorithms for adjusting electric drives, which helped not only to minimise overheating of the dough but also to improve its texture.

K. Kansou *et al.* (2013) studied changes in the porosity and stability of dough depending on kneading conditions. Optimal mixing parameters have been found to be key to preventing excessive dough density or loss of stability during the ageing process. In the study of the OptiMix-360 system, porosity stability was achieved due to the uniform distribution of mechanical energy and hydration, which confirms the authors' conclusions about the need to provide such conditions for improving the quality of production.

Research by A. Wooding *et al.* (1999) revealed the dependence of dough strength on mixing intensity. The results obtained in this study also showed that precise control of the kneading intensity in the OptiMix-360 system helps to maintain the flexibility of the gluten mesh, which positively affected its ability to withstand mechanical processing during the moulding of products. In addition, the use of an expert system to monitor key parameters, as described in K. Kansou *et al.* (2014), similar to the approaches used, allows for precise process control and maintenance of dough stability under variable production conditions. The study by A. Van der Mijnsbrugge *et al.* (2016) focused on the distribution of the gluten phase as a function of mixing parameters. In turn, OptiMix-360, due to the use of appropriate equipment, ensured a uniform distribution of gluten, which is confirmed by the stability of the dough structure at all stages of the process. In addition, the implemented automation made it possible to minimise the impact of the human factor.

Innovations in mixing weak dough are presented in the study by A. Parenti *et al.* (2013), which investigated mixing control for weak wheat dough using sourdough. OptiMix-360 demonstrated a similar approach, providing precise control of rheological properties even in complex formulations. This proves that the introduction of automation in the system allows maintaining the consistency of the dough regardless of the type of flour and recipe. S. Peighambardoust *et al.* (2006) emphasised the role of the initial mixing phase in the formation of the dough structure. The use of TORNADO-2 premixer in the implemented technology created optimal conditions for the initial combination of ingredients and the development of gluten mesh, which ensured a high-quality initial stage of kneading. An equally significant role is played by the introduction of sensor technologies in food production. The study by R. Morales *et al.* (2022) confirms that the integration of sensor systems for monitoring parameters such as humidity, temperature, and ingredient flow rate contributes to process stability. Similar principles are implemented in OptiMix-360, which made it possible to ensure high dosing accuracy (<0.1%) and control of process parameters in real time.

Automated control of technological processes, based on modern regulatory algorithms, is one of the key approaches to improving product quality. Research by P.K. Juneja *et al.* (2021) proved the effectiveness of such methods, which is fully consistent with the practice used in OptiMix-360. The use of adaptive control algorithms ensured high dosage accuracy and stability of key technological parameters, reducing the influence of the human factor and increasing the repeatability of product characteristics. J. Lee *et al.* (2023) confirmed that the use of data processing algorithms in the food industry significantly improves control over production processes. In the case of OptiMix-360, the use of automatic analysis of process parameters and algorithmic control of the dough composition contributes to the achievement of high production stability and quality of the final product, which corresponds to general trends in the field of smart production. In addition, research by N.J. Watson *et al.* (2021) highlighted the need to combine sensor control with algorithmic control to ensure process stability. The implementation of these principles in OptiMix-360 allowed achieving uniform kneading and high dosing accuracy, which meets modern requirements for food production automation.

Ultimately, research by H.J. Kaur *et al.* (2024) confirmed the effectiveness of automated solutions in ensuring product quality stability and optimising production costs. OptiMix-360 implements similar principles, namely gravimetric dosing, automated control of the kneading process, and adaptive parameter control, which significantly reduces material losses and ensures controlled dough quality. The use of the GraviFlow Master system ensured dosing accuracy with a deviation of less than 0.1%, which contributed to the stability of the dough composition. TORNADO-2 premixer optimised the process of moistening flour and forming a gluten mesh, which improved the texture and strength of the final product. The ProMix D-Helix continuous dough mixer helped to evenly distribute mechanical energy and avoid overheating of the dough, which ensured the uniformity of its structure. In addition, automated control based on the Siemens S7-1500 programmable logic controller allowed real-time monitoring of humidity, temperature and proportions of ingredients, which helped to minimise changes in the quality of the final product.

Thus, the results obtained showed that the OptiMix-360 system not only meets the current requirements of the bakery industry, but also demonstrates significant potential for improving kneading processes. Comparison with other studies has highlighted the importance of integrating automated solutions such as stable temperature maintenance, precise hydration, and uniform distribution of mechanical energy. Thus, the results of the study confirmed the feasibility of using OptiMix-360 for industrial production, offering new approaches to solving rheological and technological problems.

Conclusions

The results of the study confirmed the efficiency and innovation of implementing the OptiMix-360 system in industrial dough production. The combination of high-tech equipment such as GraviFlow Master, TORNADO-2, and ProMix D-Helix allowed significantly improving the quality of dough and optimising production processes. Compared to conventional methods, the continuous nature of the process, automation and adaptability of system settings ensured an increase in productivity up to 1,500 kg/h, a reduction in energy consumption by 30%, and a stable quality of each batch of dough. This helped to minimise losses due to deviations in consistency and ensure a uniform structure, which is especially important for large-scale industrial production.

The use of the GraviFlow Master gravimetric dosing system helped to increase the dosing accuracy to <0.1%, which ensured the stability of the dough composition. The TORNADO-2 premixer allowed optimising the hydration of flour, and the active formation of gluten mesh, which is critical for the texture and strength of the final product. Due to its design features, the ProMix D-Helix dough mixer maintained a stable temperature and uniform distribution of mechanical energy, which prevented overheating of the dough and disruption of its structure.

The main advantages of the system are high energy efficiency, easy operation, and reduced dependence on the human factor through the integration of automated solutions, including HMI and remote monitoring. Stable process parameters provided by an automated control system contributed to high productivity and quality. However, the system has certain limitations, which include the high cost of implementation, the need for specialised training of personnel, dependence on the accuracy of settings and sensitivity to external factors such as vibrations and pressure fluctuations. The results obtained showed the potential of the OptiMix-360 system for wide implementation in the food industry, in particular, in the bakery industry. Its use has significantly increased production efficiency, improved the quality of finished products and reduced costs, which makes it an important element of the technological process.

A limitation of this study was the use of only one type of technology, which may limit the possibility of comparison with other existing methods in other areas of the food industry. The study also did not address the long-term economic effects of introducing new technologies in different market economies. The results also open up prospects for further research. One of the areas is a detailed analysis of the impact of the system on various types of raw materials, in particular, whole grain or gluten-free flour. It is also worth investigating how the introduction of such systems can affect the taste characteristics of products and their nutritional value. In addition, integrating the system with platforms based on the Internet of Things or artificial intelligence can improve the data analysis process and automate adjustments. Developing more affordable system options for small businesses is also an interesting area.

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Conflict of Interest

None.

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Автоматизована система OptiMix-360 для безперервного замішування тіста: технічні рішення та ефективність

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Анотація. Підвищення ефективності та стабільності промислового виробництва тіста можливе завдяки впровадженню інноваційних технологій, які оптимізують якість і знижують витрати. Метою цього дослідження було оцінити ефективність системи OptiMix-360 для промислового виробництва тіста через інтеграцію таких технологій, як гравіметричне дозування, преміксери та тістоміси, визначити її вплив на покращення продуктивності та якості кінцевого продукту. Методологія дослідження базувалася на експериментальному підході, який передбачав оцінку ефективності системи OptiMix-360 у порівнянні з традиційними методами шляхом вимірювання параметрів якості продукції та продуктивності процесів за різних умов експлуатації. Здійснено аналіз ефективності обладнання GraviFlow Master, TORNADO-2 та ProMix D-Helix на основі показників продуктивності, енергоспоживання, точності дозування, якості кінцевого продукту при впровадженні цих технологій у виробничий процес. Впровадження системи OptiMix-360 дозволило досягти суттєвого підвищення продуктивності до 1500 кг/год, зменшення енергоспоживання на 30 %, а також стабільної якості кожної партії тіста. Гравіметрична система дозування забезпечила точність <0,1 %, що поліпшило стабільність складу, тоді як преміксер TORNADO-2 покращив процес зволоження борошна і утворення клейковини, що позитивно позначилося на текстурі та міцності готового продукту. Процес виробництва був стабілізований, вдалося мінімізувати коливання в якості продукції завдяки автоматизації та адаптивним налаштуванням. Отримані результати підтвердили ефективність впровадження системи OptiMix-360 у виробничу практику. Технологія забезпечила не тільки покращення якості тіста, але й зменшення витрат на енергоспоживання та підвищення продуктивності. Використання системи OptiMix-360 у харчовій промисловості, має високий потенціал для покращення ефективності виробництва, зменшення витрат на енергію та забезпечення стабільної якості продукції

Ключові слова: харчова промисловість; реологія; клейковина; глютен; хлібопекарська галузь