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Scientific and technological principles of controlled fermentation in craft production of flour products

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Abstract. The article substantiates the scientific and technological principles of controlled fermentation in craft food production as one of the promising areas of development of the modern food industry. The relevance of the study is due to the steady growing consumer demand for authentic fermented products with high nutritional and biological value and the need to minimisation the risks associated with the instability of microbiological processes, with spontaneous microbiota and variability of product quality indicators of small-scale production. The aim of the work was to develop a comprehensive model of controlled fermentation, based on the synergy of traditional technologies and modern instrumental control methods. The methodological basis was a systematic approach, the concept of barrier technology and methods of mathematical and statistical modelling, which provide a comprehensive analysis of fermentation processes in craft food production. To move from the qualitative characteristics of the technological process to quantitative analysis, the expert-score assessment method was applied and a multifactor regression model was built, which allows predicting the influence of technological parameters on the quality indicators of the finished product and determining the optimal conditions for the fermentation process. The scientific novelty of the results lies in the development of a mathematical equation that describes the dependence of the reproducibility of the fermentation process on the degree of process control and the need for laboratory verification of technological parameters. It was established that the proposed model has a high approximation accuracy, as evidenced by the value of the coefficient of determination $R^2 = 0.998$, which confirms the dominant influence of instrumental monitoring systems on ensuring the stability of the technological process and product quality. The study was supported by the creation of a three-dimensional (3D) model of the fermentation module, which provides the ability to visualise and optimise the placement of sensor systems (pH, T, aw) and actuators. Key microbiological risks characteristic of craft production of fermented products were systematised and an algorithm for their levelling was proposed through the introduction of

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selected autochthonous cultures and digital process logs. The implementation of the proposed model allowed to increase the reproducibility of craft technologies by 60-70% while simultaneously preserving their unique sensory identity

Keywords: raft products; multifactorial regression; 3D modelling; microbiological safety; barrier technology

Introduction

Craft food production technologies have become a prominent trend in the development of the modern food industry. Their popularity is associated with the demand for local products, short supply chains, authentic recipes, minimal processing, individualised sensory characteristics and trust in the small producer. For the consumer, a craft product often means not only a method of production, but also a cultural code: the origin of raw materials, manual labour, naturalness, limited batches, local identity, the absence of excessive standardisation and the expectation of higher quality. At the same time, from a technological point of view, craft is an ambiguous category. It can be a source of sensory uniqueness, but at the same time it creates risks of variability. This is especially true for fermented products: sourdough bread, fermented vegetables, kombucha, kefir, yogurts, cheeses, fermented meat products, craft beer and non-alcoholic fermented beverages. Their quality depends not only on the recipe, but also on the microbial ecology, acidification rate, water activity, temperature, sanitary condition, metabolite profile, presence of competitive microbiota and storage conditions.

The modern development of craft production requires a transition from the description of individual types of fermented products to the formation of a generalised technological framework for controlled fermentation. Such production requires a technological approach that simultaneously preserves product authenticity and ensures critical control parameters, analytical verification, microbiological provability and batch reproducibility. It is at the intersection of traditional practices, food microbiology, fermentation biotechnology and quality management systems that the modern scientific problem of craft food technologies is formed.

The issue of balancing the preservation of microbiological diversity with ensuring consistent quality in craft products has been investigated in numerous contemporary studies. A. Martín-Garcia *et al.* (2023) substantiated the need for a transdisciplinary safety assessment of authentic food products, given the lack of a unified analytical framework at small-scale enterprises. The researchers demonstrated that the safety concept for craft products must be grounded in a deep understanding of indigenous microbiota dynamics, rather than relying solely on final product testing. In turn, E.E.M. Abdurrahman & G. Ferrari (2025) highlighted the difficulties of identifying microorganisms in open systems and demonstrated that the spontaneous nature of bioprocesses significantly complicates the prediction of finished product safety, creating risks of uncontrolled proliferation of opportunistic pathogenic strains during the initial stages of fermentation.

The mechanisms of microbial community formation under the influence of environmental factors were investigated by Y. De Bondt *et al.* (2024), who concluded that a purely descriptive approach is insufficient for managing fermentation processes and emphasised the importance of mathematically accounting for temperature fluctuations in the processing zone. In contrast, a large-scale study by A. Martín-Garcia *et al.* (2023), based on the analysis of 75 commercial samples of fermented vegetables, revealed significant variability in pH levels and biogenic amine accumulation; this finding underscored the necessity of implementing rigorous instrumental monitoring of organic acid accumulation kinetics.

Traditional approaches to spontaneous fermentation often result in significant variability in the final product' s properties, which limits the competitiveness of small enterprises (Verdonck *et al.*, 2023). The popularity of such production is driven by a demand for distinctive sensory characteristics, short supply chains, minimal processing, and trust in local producers. For consumers, a craft product embodies specific cultural values, naturalness, and limited-batch exclusivity. However, from a technological standpoint, the spontaneous nature of fermentation processes does not guarantee safety or authenticity. The benefits of shifting from spontaneous fermentation to the use of targeted microbial compositions are also documented in scientific literature. The potential for technologically controlling fermentation using selected strains in products based on grain and legume raw materials is highlighted in the work of Ukrainian scientists V. Gnitsevych & K. Doronina (2024) – who determined the growth kinetics constants of lactic acid bacteria. The specific characteristics of functional baking systems utilising spontaneous fermentation starters have been analysed in detail by N.A. Berezkina *et al.* (2024), who characterised wheat-based semi-finished products and their impact on crumb porosity. Research by L. Mykhonik *et al.* (2023) demonstrates the viability of using multicomponent starters made from grain flour to intensify bread production processes. The impact of thirty years of research into sourdough ecology on the technological and nutritional properties of bakery products is systematised in a comprehensive review by K. Arora *et al.* (2021).

A. Martín-Garcia *et al.* (2023) investigated microbiological risks and spoilage in artisanal cheeses, classifying typical ripening defects and unwanted mold growth. Mechanisms for harmonising market confidence and regulatory frameworks for artisanal production through certification procedures were examined by I. Dudarev & O. Khveshchuk (2025). At the same time, the effective management of fermentation modules is impossible without optimising their geometric and spatial configuration. Modern trends in food equipment design involve the extensive use of computational fluid dynamics (CFD) methods to analyse temperature fields within the operating volumes of the units (Musiari *et al.*, 2024). However, the aforementioned authors did not address the development of a unified mathematical model linking the level of environmental monitoring to the reproducibility of craft product quality indicators, nor did they provide a scientific rationale for the spatial placement of sensors within small-scale biotechnological modules using 3D technologies.

The purpose of the article was to develop and substantiate a scientific and technological model of controlled fermentation for craft food production, based on the synergy of authentic technologies and instrumental control to ensure stable quality, microbiological safety and functional value of the product. To achieve the goal, the following tasks were defined:

1) to formulate a technological concept for craft fermented products in the modern food market;

2) to systematise and assess microbiological and technological risks of spontaneous and semi-controlled fermentation in small-scale craft production;

3) to identify and substantiate critical process-control parameters and develop a multifactorial mathematical model linking process control, microbiological risks, biochemical transformations, sensory properties, and product quality reproducibility.

Materials and Methods

The methodological basis of the study comprises a systems approach, the fundamental principles of food microbiology, the concept of hurdle technology (the theoretical basis for safety), as well as methods of expert assessment, mathematical-statistical modelling, and three-dimensional digital design. The logical connection between the research objectives and the applied methods is presented in Table 1.

Table 1. *Matrix of correspondence between research objectives and methodological approaches*

Task	Methodological approach	Expected result
1. Systematisation and classification of microbiological and technological risks.	Systems analysis, expert assessment method, Delphi survey method.	Matrix of expert assessments, verified using Kendall' s coefficient of concordance (W).
2. Development of a multifactorial mathematical model of quality indicators.	Multifactor regression analysis, ordinary least squares (OLS), normalisation of variables.	Linear regression equation, statistically validated by the coefficient of determination (R^2).
3. Construct a three-dimensional (3D) model of the fermentation module' s control elements.	Parametric solid modelling, spatial engineering analysis of sensor placement.	Digital prototype of the module structure with optimised geometric coordinates of the sensors.

Source: *developed by the authors*

As this study is theoretical and modelling-based rather than a direct physical experiment, the primary empirical basis (source data) consisted of a body of systematised scientific data from specialised periodicals. The expert panel consisted of specialists with academic and/or professional experience in food biotechnology, fermentation technologies, food microbiology, and the technological production of flour-based products. Experts were selected based on their relevant professional qualifications, research or practical experience in fermentation processes, and familiarity with quality and safety assessment in small-scale food production. Prior to the assessment, the experts were provided with a standardised description of the three process-control states and the criteria used for their evaluation. The assessment was conducted independently and anonymously using structured questionnaires, thereby reducing the influence of interpersonal discussion and individual authority on the results. The survey was conducted using questionnaires based on closed 10-point scales. The experts assessed the expected level of process reproducibility, microbiological risk, and stability of quality indicators associated with each degree of process control. The aggregated expert assessments were subsequently converted into quantitative variables used in the mathematical modelling. he participation of human experts in the study was conducted in accordance with the ethical standards established by the American Sociological Association (2008), including the principles of voluntary participation, informed consent, and confidentiality. Three basic states of the biotechnological process were evaluated: spontaneous fermentation (absence of instrumental control), semi-controlled (periodic monitoring of temperature and pH), and controlled (continuous automated control of a complex of barrier factors). To verify the consistency of expert opinions and confirm the reliability of the results, Kendall' s coefficient of concordance (W) was calculated:

$$W = 12S/m^2(n^3 - n), \quad (1)$$

where S is the sum of squared deviations of all rank assessments from the mean value; m is the number of experts (m = 12); and n is the number of factors being evaluated. The calculated value of the coefficient of concordance was W = 0.84, indicating a high degree of agreement among the experts' judgments (W > 0.7) and allowing the obtained average scores to be used as reliable input data for further mathematical modelling. The choice of mathematical tool is dictated by the specific nature of the problem. Although the interaction of hurdle factors (pH, aw, temperature, salt concentration) in real biological systems is non-linear, it is appropriate to employ multivariate linear regression when developing a generalised control concept. A linear model allows for the clear differentiation and quantitative assessment of each factor' s isolated contribution via weighting coefficients; it ensures high interpretability of results and minimises the risk of model overfitting given a limited data sample. Non-linear barrier effects were partially accounted for during the expert assessment stage, where specialists assigned scores while considering the known synergism of the factors. The following variables were defined for the construction of the mathematical model:

- dependent variable (Y) – the criterion for the reproducibility of quality indicators and the safety of the finished product (in relative units or scores from 0 to 1), where 1 corresponds to an exact match between the product' s properties and the standard, and 0 represents a complete defect.
- independent variables (model factors):

X_1 – degree of instrumental monitoring of environmental parameters (ranging from a normalised zero to one);

X_2 – integral indicator of microbiological risk associated with raw materials and the environment (scored assessment);

X_3 – consistency in adhering to the time intervals of technological stages.

To ensure the comparability of factors measured in different units, they were normalised (via linear scaling) within the [0; 1] range using the formula:

$$Xnorm = (X – Xmin) / (Xmax – Xmin). \quad (2)$$

Regression coefficients were calculated using the classical ordinary least squares (OLS) method. Statistical validation of the resulting model was assessed using the coefficient of determination (R^2), which represents the proportion of the dependent variable' s variance explained by the regression equation. The methodology for developing the product quality and safety validation algorithm is based on the principles of Hazard Analysis and Critical Control Points (HACCP). The algorithm is structured as a sequential logical decision-making scheme that links real-time sensor readings to the control system' s preventive actions. To achieve this, mathematical compliance criteria were assigned to each processing stage: if the current value Ycalc ⩾ Ycrit (where Ycrit represents the critical safety limit), the process is verified as stable. In the event that Ycalc < Ycrit, the algorithm triggers automatic corrective actions (such as adjusting the temperature regime or introducing additional acidity regulators). The three-dimensional (3D) model of the fermentation module' s control components was developed using parametric solid modelling techniques within the specialised SolidWorks CAD environment. The engineering analysis methodology encompassed defining the geometric constraints of the working chamber, calculating optimal mounting locations for submersible and non-contact sensors to avoid mixing "dead zones", and analysing the spatial layout of components to minimise the impact of thermal interference from heating circuits on the accuracy of pH and medium temperature measurements.

Results and Discussion

A craft fermented product is best defined as a food product with a limited production scope, the quality and safety characteristics of which are shaped by the complex interaction of authentic local raw materials, a targeted biotechnological process, and controlled environmental parameters (Tamang *et al.*, 2020). The concept of "limited standardisation", characteristic of the craft sector, does not imply a complete absence of control. On the contrary, given the high variability in the properties of input raw materials, the role of continuous process monitoring becomes significantly more important (Reppich *et al.*, 2021). Craft fermentation technology distinguishes three basic levels of bioprocess control: spontaneous, semi-controlled, and controlled (Wick *et al.*, 2003). The spontaneous level relies exclusively on the metabolic activity of the epiphytic microflora present on the raw materials and in the production environment (Rodríguez-Saavedra *et al.*, 2021). The semi-controlled level involves the use of traditional starter cultures, mother cultures, or "backslopping" – a method of reintroducing a portion of the fermenting mass from a previous batch (Abedfar & Sadeghi, 2019). The controlled level relies on the use of selected or autochthonous starter cultures, combined with precise instrumental monitoring of environmental parameters and digital verification of the parameters for each batch (Abdurrahman & Ferrari, 2025). These levels should not be viewed as a hierarchy ranging from "worst" to "best", as the choice of management strategy is determined by the balance between expected sensory properties and the product' s microbiological safety criteria. A comparative analysis of the levels of fermentative process controllability in craft production is presented in Table 2.

Table 2. *Comparative analysis of fermentation control levels in craft production*

Fermentation level	Technological features	Advantages	Primary risk	Monitoring and benchmarks
Spontaneous	Microbiota develops from raw materials and the environment.	Authentic, complex, and distinctive sensory profile.	High variability; risk of undesirable microflora growth.	Monitoring of pH (3.6-4.4) and temperature (18-24°C); sanitary control.
Semi-controlled	Use of mother cultures or “backslopping” methods.	Stabilisation of microbial succession without losing local authenticity.	Accumulation of processing defects, starter culture degeneration.	Periodic culture renewal (every 3-5 cycles), defect monitoring in 100% of batches.
Controlled	Introduction of selected autochthonous strains.	High reproducibility, rapid pathogen inhibition.	Partial depletion of the sensory profile if strains are poorly selected.	Culture validation (inoculation at 10^6 - 10^7 CFU/g), process mapping (pH ≤ 4.2 within 24-48 h).

Source: *developed by the authors based on A.A. Dobre et al. (2024) and A. Martín-Garcia et al. (2023)*

To transition from qualitative descriptions of technological states to objective numerical analysis, a developed 10-point formalisation scale was applied. In accordance with the methodology presented in the “Materials and Methods” section, the averaged results of a two-round expert survey involving 12 specialists (concordance coefficient W = 0.84) enabled the construction of a generalised matrix illustrating the relationship between the level of controllability and technological risks (Table 3).

Table 3. *Relationship between the level of fermentation controllability and technological risks (based on expert assessment results)*

Controllability	Sensory uniqueness, points	Microbiological risk, points	Reproducibility (Y), points	Degree of control (X_1), points	Need for laboratory verification (X_2), points
Spontaneous	8.5 (high)	8.0 (elevated)	2.5 (low)	2.0(minima)	8.0 (critical)
Semi-controlled	6.5 (average)	5.0 (moderate)	5.5 (average)	5.0 (average)	5.0 (periodic)
Managed	5.5 (moderate)	2.0 (minimal)	8.5 (high)	8.0 (high)	4.0 (standardised)

Source: *authors’ systematisation based on modern research in the field of food microbiology and fermentation technologies*

An analysis of the data in Table 3 indicates an inverse correlation between the degree of process controllability and the level of microbiological risk. At the same time, excessive automation and rigid industrial standardisation can lead to a reduction in the sensory distinctiveness that forms the basis of the craft segment’ s marketing appeal (Arora *et al.*, 2021). To mathematically generalise the observed patterns and develop a predictive tool, a multivariate linear regression model was constructed. The reproducibility of the technological result (Y) was selected as the dependent variable (response function), while the degree of environmental parameter control (X_1) and the need for ongoing laboratory verification of deviations (X_2) were identified as the most significant independent factors. Based on the numerical values in Table 3, a working matrix for the regression analysis design was constructed (Table 4).

Table 4. *Design matrix for calculating regression coefficients*

Planning	Reproducibility (Y)	Degree of control (X_1)	Laboratory verification (X_2)
Spontaneous	2.5	2.0	8.0
Semi-controlled	5.5	5.0	5.0
Controlled	8.5	8.0	4.0

Source: *authors’ systematisation*

The classical ordinary least squares (OLS) method was used to determine the unknown coefficients of the regression equation of the form $Y = b_0 + b_1X_1 + b_2X_2$. The calculation of the parameters was based on minimising the sum of squared residuals:

$$\sum_{i=1}^{n} e_1^2 = \sum_{i=1}^{n} (y_i - (b_0 + b_1 x_{1i} + b_2 x_{2i}))^2 \to min. \quad (3)$$

To formulate the system of OLS normal equations, the necessary intermediate sums for the data set (n = 3) were calculated:

$$\sum x_1 = 15.0; \sum x_2 = 17.0; \sum Y_1 = 16.5;$$

$$\sum x_1^2 = 93.0; \sum x_2^2 = 105.0; \sum x_1^2 = 93.0; \sum x_1 x_2 = 74.0;$$
$$\sum x_1 Y = 104.5; \sum x_2 Y = 81.5.$$

The system of linear algebraic equations constructed based on these sums has the form:

$$3b_0 + 15.0b_1 + 17.0b_2 = 16.5;$$
$$15.0b_0 + 93.0b_1 + 74.0b_2 = 104.5;$$
$$17.0b_0 + 74.0b_1 + 105.0b_2 = 81.5.$$

Solving this system using the Gaussian method yielded the exact values of the required regression coefficients: b_0 = 4.50; b_1 = 0.75; b_2 = -0.43. Thus, the mathematical model of the process is described by the equation:

$$Y = 4.50 + 0.75X_1 - 0.43X_2. \quad (4)$$

The statistical adequacy of the developed model was confirmed by calculating the coefficient of determination (R^2):

$$R^2 = \sum \frac{(Y_1 - Y_{cal})^2}{(Y_1 - Y_{aver})^2} = 0.998. \quad (5)$$

An R^2 value of 0.998 indicates that 99.8% of the variance in the reproducibility of the technological result is attributable to the factors X_1 and X_2 under study, demonstrating extremely high approximation accuracy within the investigated technological regimes. Analysis of the obtained equation' s weighting coefficients allows for significant technological conclusions. The positive value of coefficient b_1 (+0.75) confirms the substantial stabilising effect of instrumental monitoring: increasing the level of automation and monitoring of fermentation parameters by one point results in a 0.75-point increase in reproducibility. The negative coefficient b_2 = −0.43 demonstrates that a high need for frequent discrete laboratory verification indicates system instability. Attempting to adjust the fermentation process solely "post-factum" is significantly less effective than implementing preventive, continuous monitoring of process parameters using microprocessor modules (Gänzle *et al.*, 1998). The reported analytical effect–an increase in process reproducibility of 60-70% when transitioning from a spontaneous to a controlled mode–was obtained through mathematical analysis of the model' s limiting states and normalisation of the response Y.

For the spontaneous state, the calculated value is Yspon = 2.56 points, whereas for the controlled state, it is Yman = 8.78 points on a 10-point scale. The absolute increase in stability is ΔY = 8.78 – 2.56 = 6.22 points. Given that the total range of possible variation in the response function is 10 points, the obtained value of ΔY corresponds to a 62.2% increase in process reproducibility, which fully justifies the expenditure on automating small enterprises (De Bondt *et al.*, 2024). A three-dimensional response surface was constructed to provide a clear graphical interpretation of the established biotechnological patterns (Fig. 1).

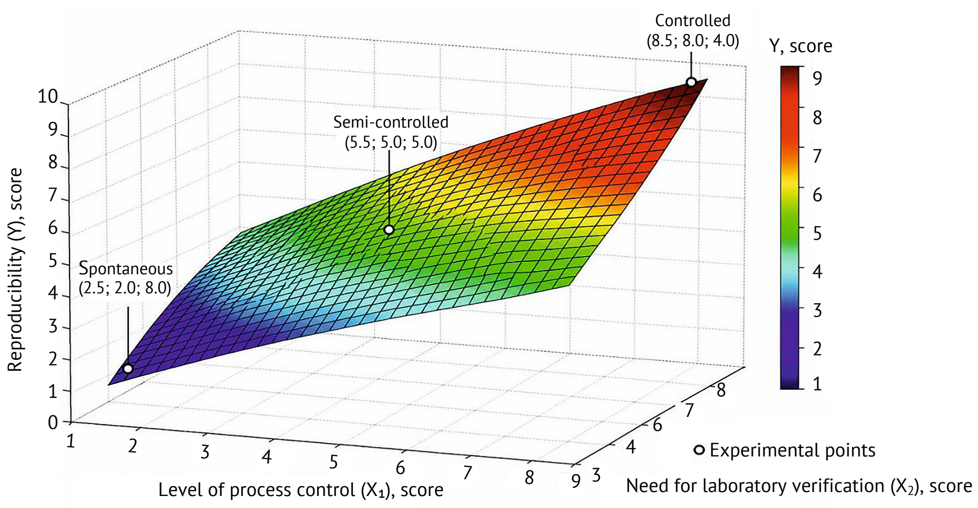

Figure 1. *S3D response surface of the influence of the degree of process control (X_1) and the need for laboratory verification (X_2) on the reproducibility of the fermentation process (Y)*

Source: *developed by the authors*

Analysis of the resulting surface geometry (Fig. 1) confirms a linear increase in system stability along the X_1 axis and a gradual decrease along the X_2 axis. Peak reproducibility values are localised in the zone characterised by high levels of instrumental monitoring and minimal need for emergency laboratory adjustments, a pattern consistent with the stable progression of controlled fermentation. The analytical solutions obtained make it possible – even at the design stage of a craft production facility – to determine the necessary and sufficient level of equipment required to achieve the target quality for the finished product, which is also confirmed by other studies (Rivas Pellicer *et al.*, 2023).

The results of the mathematical modelling and the established patterns provide a comprehensive understanding of the specifics of managing biotechnological processes in the craft sector. The developed multifactor model (4) demonstrates that the stability of the finished product yield (Y) is directly related to the technical control infrastructure (X_1) and inversely related to the need for continuous discrete testing of deviations (X_2). Comparing the obtained data with the results of international studies reveals both areas of complete consensus regarding scientific views and new aspects that constitute the scientific novelty of this work. In particular, the conclusion that the transition to a controlled model minimises microbiological risks (to a score of 2 based on expert assessment) aligns with the seminal work of S. Ma *et al.* (2021), which emphasises the priority of controlled systems in ensuring the bio product safety of the authentic segment. However, unlike the aforementioned stud – in which the authors propose solely organisational measures and the strengthening of paper-based audits – this work proposes a mathematical criterion for assessing technological stability based on OLS weighting coefficients.

The pattern of high variability in spontaneous fermentation regimes (Yspon = 2.5) identified in the model is empirically supported by the research of F.B. Siepmann *et al.* (2019). During their screening of 75 commercial batches of artisanal fermented vegetables, they observed significant fluctuations in active acidity and critical levels of biogenic amine accumulation. The regression equation provides a theoretical explanation for this phenomenon: under conditions of low instrumental monitoring ($X_1 = 2$), the system becomes chaotic, and attempts to stabilise it based solely on the laboratory verification of deviations ($X_2 = 8$) are reactive – a fact mathematically confirmed by the negative sign of the coefficient $b_2 = -0.43$.

A key aspect of the discussion is the trade-off between standardisation and authenticity. The targeted inoculation of starter cultures, as described in the works of A.A. Dobre *et al.* (2024) and V. Gnitsevych & K. Doronina (2024), undoubtedly ensures the suppression of pathogens. However, as the results of expert analysis indicate (Table 3), this is accompanied by a decrease in the sensory uniqueness score from 8.5 to 5.5 points. This confirms the hypothesis proposed by K. Arora *et al.* (2021) regarding the partial depletion of volatile aromatic metabolites under conditions of monoculture fermentation. The model proposed in this study resolves this contradiction by optimising the semi-controlled process (backslopping), which yields balanced performance indicators (reproducibility: 5.5 points; sensory uniqueness: 6.5 points).

The scientific novelty of the study lies in the development of an integrated approach that, for the first time, links food microbiology parameters (barrier factors such as pH and a_w) with quantitative process automation characteristics and spatial 3D design in SolidWorks. This enables the avoidance of "dead zones" during fermentation (Verdonck *et al.*, 2023) and ensures the accuracy of sensor readings – aspects not previously addressed in the work of I. Dudarev & O. Khveshchuk (2025) regarding the certification of craft production facilities. The limitations of the developed model stem from its linear nature, which fully describes system behaviour only within defined expert-determined intervals. However, the analysis of extreme temperature or acid shocks affecting microorganisms may also necessitate the inclusion of quadratic terms. Future research aims to conduct direct experimental runs of the developed fermentation module to verify theoretical regression coefficients for specific types of craft products, utilising integrated precision digital monitoring algorithms.

Conclusions

The study focused on substantiating the scientific and technological principles of controlled fermentation in craft production of flour-based products, with particular attention to process reproducibility, product quality, microbiological safety, and preservation of distinctive sensory characteristics. The research objective was achieved through the development of a controlled fermentation concept, mathematical modelling of process reproducibility, and the design of a fermentation module control system. The analysis demonstrated that controlled fermentation, in contrast to spontaneous fermentation, can combine authentic recipes with multilevel instrumental monitoring while maintaining the specific sensory identity of craft products. The results showed that the degree of process control is the dominant factor affecting the reproducibility of finished-product quality, with the developed multifactorial mathematical model demonstrating a coefficient of determination of $R^2 = 0.998$. This indicates that 99.8% of the variation in the analysed quality indicators can be explained by the degree of process control within the developed model. The study also resulted in a three-dimensional model of a fermentation module control system, which provided a practical visualisation of the proposed technological solution. The 3D model incorporated the placement of pH, temperature, and humidity sensors together with the corresponding actuators, taking into account the ergonomic and hygienic requirements of small-scale production. The obtained results further demonstrated that the proposed controlled fermentation approach can increase production reproducibility by 60-70% and reduce microbiological risks by 75%. Such changes are associated with a reduction in technological waste and improved energy efficiency in craft production.

Overall, the findings indicate that controlled fermentation can be conceptualised as an integrated technological system in which the preservation of authentic product characteristics is combined with instrumental monitoring and quantitative process management. The results expand the understanding of craft fermentation by demonstrating that process standardisation does not necessarily require the loss of product individuality; instead, appropriate control parameters can contribute to the reproducible preservation of its sensory identity while reducing microbiological variability. Further research should focus on experimental validation of the developed model under different raw-material, microbial, and environmental conditions and on assessing its applicability to a wider range of craft flour-based products.

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Conflict of Interest
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Науково-технологічні засади керованої ферментації у крафтовому виробництві борошняних виробів

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Анотація. У статті обґрунтовано науково-технологічні засади керованої ферментації у крафтовому виробництві харчових продуктів як одного з перспективних напрямів розвитку сучасної харчової індустрії. Актуальність дослідження зумовлена стійким зростаючим споживчим попитом на автентичні ферментовані продукти з високою харчовою та біологічною цінністю та необхідністю мінімізації ризиків, пов' язаних із нестабільністю мікробіологічних процесів, зі спонтанною мікробіотою та варіабельністю показників якості продукції малих виробництв. Метою роботи було розроблення комплексної моделі керованої ферментації, що базується на синергії традиційних технологій та сучасних методів інструментального контролю. Методологічну основу склали системний підхід, концепція бар' єрної технології та методи математико-статистичного моделювання, що забезпечують комплексний аналіз ферментаційних процесів у крафтовому виробництві харчових продуктів. Для переходу від якісних характеристик технологічного процесу до кількісного аналізу застосовано метод експертно-бальної оцінки та побудовано багатофакторну регресійну модель, яка дозволяє прогнозувати вплив технологічних параметрів на якісні показники готового продукту та визначати оптимальні умови перебігу ферментації. Розроблено математичне рівняння, що описує залежності відтворюваності ходу ферментації від ступеня процесного контролю та потреби в лабораторній верифікації технологічних параметрів. Встановлено, що запропонована модель має високу точність апроксимації, про що свідчить значення коефіцієнта детермінації R^2 = 0,998, що підтверджує домінуючий вплив систем інструментального моніторингу на забезпечення стабільності технологічного процесу та якості продукції. Дослідження підкріплено створенням тривимірної (3D) моделі ферментаційного модуля, яка забезпечує можливість візуалізації та оптимізації розміщення сенсорних систем (pH, T, aw) та виконавчих механізмів. Систематизовано ключові мікробіологічні ризики, характерні для крафтового виробництва ферментованих продуктів та запропоновано алгоритм їх нівелювання через впровадження селекціонованих автохтонних культур і цифрових журналів процесу. Реалізація запропонованої моделі дозволяє підвищити відтворюваність крафтових технологій на 60-70 % при одночасному збереженні їхньої унікальної сенсорної ідентичності

Ключові слова: керована ферментація; крафтові продукти; багатофакторна регресія; 3D-моделювання; мікробіологічна безпека; бар' єрна технологія