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DEVELOPMENT OF A RISK-BASED APPROACH TO MEAT PRODUCT SAFETY

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РОЗВИТОК РИЗИК-ОРІЄНТОВАНОГО ПІДХОДУ ДО БЕЗПЕЧНОСТІ М’ЯСНИХ ПРОДУКТІВ

ABSTRACT

Purpose of the work. The aim of this study is to summarise and systematically analyse contemporary risk-oriented approaches to ensuring the safety of meat products intended for children and sensitive population groups, as well as to substantiate the feasibility of using product shape and internal structure as engineering tools for reducing technological risks in the production of dried meat products.

Methodology. The methodology of the study is based on a review and analytical approach employing structural-logical, comparative and critical analysis of current scientific publications and regulatory documents: Codex Alimentarius, ISO 22000, norms of EFSA etc. related to food safety management. The analysis is conducted from a risk-oriented perspective, taking into account the multi-barrier concept, the role of water activity, dehydration kinetics, and the influence of product geometry and internal structure on the formation of microbiological stability in meat products.

Scientific novelty. Scientific novelty lies in the development of a generalised conceptual model in which the shape and internal structure of dried meat products are considered as active engineering factors for risk management. An interpretation of safe-by-design principles in food technologies is proposed as an applied mechanism of “built-in safety”, enabling the reduction of technological risks through product and process design rather than exclusively through formulation- or ingredient-based solutions.

Conclusions. The conclusions indicate that, for meat products intended for children and sensitive population groups, a risk-oriented approach should be combined with engineering control of product shape and internal structure. Such an approach contributes to reducing the duration of product exposure to potentially hazardous conditions, levelling water activity profiles, and decreasing dependence on preservative additives without compromising safety and quality.

Key words: risk-oriented approach, meat product safety, safe-by-design, water activity, structural design of food products

АНОТАЦІЯ

Мета роботи. Мета роботи полягає в узагальненні та системному аналізі сучасних ризик-орієнтованих підходів до забезпечення безпечності м’ясних продуктів, призначених для дітей та сенситивних груп населення, а також в обґрунтуванні доцільності використання форми та внутрішньої будови продукту як інженерного інструменту зниження технологічних ризиків у процесах виготовлення сушених м’ясних виробів.

Методологія. Методологія дослідження базується на оглядово-аналітичному підході з використанням структурно-логічного, порівняльного та критичного аналізу сучасних наукових публікацій і нормативних документів: Codex Alimentarius, ISO 22000, документів EFSA та ін., присвячених управлінню безпечністю харчових продуктів. Аналіз виконано з позицій ризик-орієнтованої логіки з урахуванням багатобар’єрної концепції, ролі активності води, кінетики зневоднення та впливу геометрії і внутрішньої структури м’ясних виробів на формування мікробіологічної стабільності.

Наукова новизна. Формування узагальненої концептуальної моделі, в якій форма та внутрішня будова сушених м’ясних продуктів розглядаються як активні інженерні чинники керування ризиками. Запропоновано інтерпретацію принципів safe-by-design у харчових технологіях як прикладного механізму «вбудованої безпечності», що дозволяє зменшувати технологічні ризики шляхом проєктування продукту та процесу, а не виключно за рахунок рецептурних або інгредієнтних рішень.

Висновки. Для м’ясних продуктів, орієнтованих на дітей та сенситивні групи населення, ризик-орієнтований підхід доцільно поєднувати з інженерним керуванням формою та внутрішньою будовою виробу. Такий підхід сприяє скороченню тривалості перебування продукту у потенційно небезпечних умовах, вирівнюванню профілю активності води та зниженню залежності від консервувальних добавок без компромісу щодо безпечності й якості.

Ключові слова: ризик-орієнтований підхід, безпечність м’ясних продуктів, safe-by-design, активність води, структурне проєктування харчових продуктів

Introduction

Ensuring the safety of food products intended for children and other sensitive population groups is one of the priority tasks of modern food science and practice. These groups include individuals with compromised immune systems, chronic diseases, metabolic disorders, as well as consumers for whom even moderate levels of conventionally acceptable food-related risks may have critical consequences. In this context, approaches to food safety for such population groups should be based not only on compliance with general regulatory requirements, but also on the principles of risk reduction at all stages of production.

Meat products, particularly dry-cured and fermented products, belong to a category of foods characterised by high technological complexity and a multifactorial nature of risk formation. Their safety is determined by a combination of physicochemical, microbiological and structural factors, among which the moisture content of the meat matrix, water activity, the duration and uniformity of drying processes, as well as the internal structure of the product play a key role. For children and sensitive population groups, even minor non-uniformities in these processes may lead to an increased level of risk, which necessitates a more precise and controllable technological approach.

Traditionally, ensuring the safety of meat products has been based on the implementation of food safety management systems, in particular HACCP, as well as on the use of ingredients with preservative effects, including nitrites. At the same time, numerous scientific publications and regulatory documents point to inherent limitations of an exclusively ingredient-based approach, especially in products intended for vulnerable population groups. In this context, the search for alternative or complementary risk-reduction tools becomes increasingly relevant, as such tools allow for a reduction in dependence on technological additives without compromising food safety.

Currently, food safety management is based on systematic risk analysis aimed at the identification, assessment and control of hazards at all stages of production, processing, storage and distribution. Scientifically grounded food safety management systems, such as HACCP, differ from traditional quality control practices in that they adopt a preventive approach focused on mitigating risks before hazardous factors can lead to adverse consequences for consumers. HACCP enables the systematic identification of hazards, the establishment of critical control points, critical limits and monitoring measures, which are essential for preventing biological, chemical and physical risks in food products, including meat products (Codex Alimentarius Commission [CAC], 2022).

In quantitative microbial risk assessment (QMRA), predictive modelling tools are increasingly applied to describe microbial behaviour under varying water activity and process conditions (Ross & McMeekin, 2003; Nauta, 2000; CAC, 1999). Such models allow not only hazard identification but also comparative evaluation of alternative technological scenarios.

According to international guidance documents, food safety management systems, including HACCP, should be implemented at all stages of the food chain – from raw materials to finished products – and should be aimed at risk reduction through scientifically justified preventive measures rather than relying solely on end-product testing (International Finance Corporation [IFC], 2020).

Within the broader risk assessment paradigm, product safety is defined as a set of measures designed to minimise the likelihood of exposure to significant hazards affecting consumer health within acceptable limits (International Organization for Standardization [ISO], n.d.). In this paradigm, a risk-oriented approach plays a key role, as it takes into account actual risk factors, their interrelationships, and the potential severity of consequences when developing control strategies.

For meat products, the risk-oriented approach must be adapted to the specific characteristics of these foods, which undergo complex physicochemical and microbiological changes during processing, storage and distribution. This applies both to thermally processed products and to dried or fermented products, where the risks associated with excessive microbial activity, component oxidation, and the formation of potentially harmful compounds may vary depending on technological parameters and the internal structure of the product (Brykova, T., 2024). In practice, risk-oriented control in the meat sector includes the analysis of biological, chemical and physical risk factors, the identification of critical control points within the technological process, and the monitoring of parameters that directly influence product safety and quality.

Modern food safety management standards, such as ISO 22000, integrate HACCP requirements into a comprehensive food safety management system and emphasise the importance of linking risk-oriented requirements with management system elements, including communication, supply chain control, traceability and hazard control (ISO, n.d.). This integration enhances the effectiveness of responses to emerging and changing risks during food production processes and ensures a clear connection between risk management activities and organisational aspects of production.

It is also important to note that a risk-oriented approach is not limited solely to the implementation of HACCP or ISO 22000. It additionally encompasses methodological tools for risk assessment, early identification of potential safety issues, forecasting of hazardous trends, and the integration of data on the impact of risks on consumer health. In particular, risk models employing quantitative assessment methods enable the prediction of risk levels and the comparison of alternative technological scenarios in meat product manufacturing (Food and Agriculture Organization of the United Nations [FAO], 2017).

The specificity of risks in meat products and the role of structural and engineering factors in their formation can be outlined as follows. Meat products, especially dry-cured and fermented products, are characterised by a multifactorial nature of risk formation, in which not only formulation but also the course of mass transfer processes within the product matrix are critical. In such systems, parameters determining the state of water – namely raw material moisture content and water activity – as well as their spatial distribution (gradients between the surface and the core), are directly related to microbiological stability and product safety. In particular, for dry and fermented sausages, water activity is considered one of the key "barriers" limiting the growth of undesirable microflora, while its reduction to a safe level is achieved through a combination of drying and salting processes (Patarata et al., 2022).

From a risk-oriented perspective, an important consideration is that hazardous zones in meat products may be localised. Even when target parameters are achieved at the product surface, internal regions may retain elevated moisture content and water activity for a longer period, thereby forming an "internal risk window" (Beňo et al., 2023). For dry-fermented products, this issue is further intensified due to the dependence of dehydration kinetics on product geometry and internal structure. Consequently, the control of water activity should account not only for its final value, but also for the sampling location and the spatial heterogeneity of this parameter within different product zones. This is supported by recent studies addressing water activity measurement practices in dried and fermented meat products and demonstrating the influence of sampling location on the interpretation of product safety. Experimental studies have demonstrated the strong dependence of Salmonella growth dynamics on water activity levels, reinforcing the need for precise spatial control of aw during drying (Gibson et al., 1988).

The classical scientific and practical framework for describing such systems is provided by the hurdle technology concept (Leistner, 2000), according to which product safety and stability are ensured not by a single factor, but by a combination of multiple barriers, including water activity, acidity, redox potential, temperature, competitive microflora and/or preservative substances. In the context of meat products, this concept is particularly valuable as it explains how a reduced dependence on individual additives, notably nitrite, can be achieved provided that other barriers are strengthened – primarily through controlled dehydration and the homogenisation of internal conditions within the product.

It should also be taken into account that technological solutions aimed at "improving" product composition – for example, reducing salt or nitrite content – may shift the balance of protective barriers and potentially increase risks if adequate compensation by other factors is not ensured, particularly water activity and drying dynamics. For dry and dry-fermented sausages, authoritative sources emphasise that water activity represents the key barrier for microbial control (Patarata et al., 2022). Accordingly, any reduction in formulation ingredients requires an engineering-controlled dehydration process and a predictable formation of water activity to maintain product safety. The predictive role of water activity in microbial stability has long been substantiated in food systems and remains one of the most reliable indicators of microbial growth limitation (Labuza & Altunakar, 2007; Fontana, 2000).

Structural and engineering factors – such as product shape, thickness, internal structure, and the characteristics of the protein–fat matrix – are critical because they directly determine diffusion path lengths and moisture transfer conditions within the product. For meat systems, it is well established that the structure of the protein matrix governs water retention, texture, and the course of transformations during technological processing (Tornberg, 2005). Consequently, modifications of external shape and internal structure can affect both mass transfer processes and the final quality attributes of the product. As a fundamental reference for substantiating the role of structure and its relationship with quality and the behaviour of meat proteins, the classical review by Tornberg is considered particularly relevant.

Within a risk-oriented framework for products intended for children and sensitive population groups, particular importance is attributed to reducing the overall dietary exposure to potentially undesirable substances, notably nitrites, while maintaining microbiological stability. EFSA highlights the technological role of nitrites, particularly their inhibitory effect on *Clostridium botulinum*, while simultaneously emphasising the need for a scientifically substantiated approach to their assessment and use (European Food Safety Authority [EFSA], 2017). In addition, quantitative exposure assessments confirm that cumulative dietary intake of nitrites remains a regulatory concern, especially in products consumed by sensitive population groups (EFSA ANS Panel, 2017). At the same time, technological strategies aimed at nitrite reduction require compensation through alternative safety barriers (Sebranek & Bacus, 2007). Risk assessment studies also analyse the contribution of meat products to long-term cumulative dietary exposure to nitrites and nitrates. This creates a basis for engineering strategies in which part of the "risk-control" function is shifted from additives to controllable process parameters and product structural characteristics.

Thus, the specificity of risks in meat products arises from the combined effects of mass transfer limitations that lead to spatial and temporal heterogeneity of water activity, structurally determined differences in diffusion pathways across various product types (minced and restructured whole-muscle products), and the need to balance safety barriers when pursuing nitrite reduction in products intended for vulnerable population groups.

In this context, the safe-by-design logic can be substantiated as an adaptation of the engineering principle of "inherent safety". That is, risk reduction is achieved not only through end-product control or intensified use of additives, but through the design of product shape and internal structure in such a way as to accelerate and homogenise dehydration, thereby reducing the duration during which the product remains in a potentially hazardous state.

In technical and regulatory disciplines, safe-by-design or safer-by-design approaches are interpreted as forms of inherent safety, whereby risks are mitigated not solely by control measures or testing of the final product, but already at the design stage through the selection of structural and constructive solutions that reduce the likelihood of hazardous scenarios throughout the product or process life cycle. This logic has been most systematically developed in the fields of material safety and nanotechnology; however, its principles are of a general engineering nature and can be adapted to food systems as “risk-informed design” or “risk-aware product design” approaches (Leistner, 2000).

As a concept in food technology, the term safe-by-design can be interpreted as an applied extension of the multi-barrier (hurdle) approach. In food engineering, a historically close analogue to safe-by-design is the concept of hygienic design of equipment and processing lines. According to this concept, equipment design should minimise contamination accumulation and ensure effective cleaning and disinfection, thereby reducing the risk of microbiological contamination. Scientific publications emphasise that poorly designed equipment structures can directly lead to microbiological and chemical hazards as well as physical contamination (Mediani et al., 2022).

For example, a classical study on risk-oriented design of aseptic processing for heterogeneous food products demonstrated that process parameters should be established based on risk assessment and product variability rather than solely on “average” technological conditions (Kabil et al., 2025). This represents a direct application of the design-for-safety logic, whereby safety is ensured through decisions made at the process design level. Consequently, engineering solutions should be regarded as an integral component of food safety systems rather than merely an auxiliary or secondary aspect.

The aim of this study is to synthesise and systematically analyse contemporary scientific approaches to ensuring the safety of meat products intended for children and sensitive population groups from a risk-oriented perspective, as well as to substantiate the feasibility of using product shape and internal structure as engineering tools for reducing technological risks in the production of dried meat products.

To achieve this aim, the following objectives were addressed:

1. to analyse current scientific approaches to risk-oriented food safety management in meat products intended for children and sensitive population groups;
2. to systematise the main technological risk factors in dried meat products, taking into account water activity and the heterogeneity of mass transfer processes;
3. to evaluate the role of product shape and internal structure as engineering factors for safety control within the multi-barrier (hurdle) concept;
4. to substantiate the applicability of safe-by-design principles in the design of meat products with reduced technological risks.

Materials and methods

This study has a review and analytical character and is based on a systematic analysis of contemporary scientific publications, regulatory documents, and analytical materials addressing food safety of meat products, risk-oriented food safety management, as well as the influence of structural and engineering factors on mass transfer processes in dried meat products.

The materials analysed in this study included peer-reviewed scientific articles from international journals; review publications on drying technologies and stabilisation of meat products; monographs and reference sources in food microbiology, food engineering, and meat technology; regulatory and scientific advisory documents of the European Union (EFSA); international food safety management standards, e.g. ISO 22000, as well as publications addressing the concepts of risk-based approaches, hygienic design, and safe-by-design in related fields.

The literature search was conducted using scientometric databases including Scopus, Web of Science, PubMed, and ScienceDirect, as well as official resources of EFSA and FAO. The search strategy was based on the following keywords: food safety, risk-based approach, meat products, dry-cured sausages, water activity, hurdle technology, safe-by-design, and food engineering.

The literature analysis was carried out using methods of structural and logical analysis (to identify relationships between technological process parameters, product structure, and safety indicators), comparative analysis (to compare different approaches to ensuring the safety of meat products), systematisation and synthesis (aimed at forming an integrated risk-oriented concept of safety management based on product shape and internal structure), as well as critical analysis (to evaluate the limitations of existing technological solutions and the possibilities of their adaptation for products intended for children and sensitive population groups).

The assessment of the role of structural and engineering factors in shaping the safety of meat products was conducted within the framework of a risk-oriented approach, which involves the identification of key risk factors – primarily microbiological-associated with water activity and dehydration heterogeneity. This approach also includes an analysis of the influence of product geometry and internal structure on mass transfer processes and on the duration for which the product remains in a potentially hazardous state. In addition, structural solutions were interpreted as elements of a multi-barrier food safety system, acting in combination with acidity, water activity, temperature, and formulation-related factors.

The synthesis of the analysis results was performed with consideration of the hurdle technology concept and safe-by-design principles, which in this study are regarded as an applied engineering interpretation of the inherent safety principle in food product development.

Results and discussion

The analytical review of contemporary scientific sources revealed that, alongside formulation- and process-related factors, product shape and internal structure play a significant role in determining the safety of dried meat products, as they directly influence mass transfer processes, the formation of water activity profiles, and microbiological stability.

Control of product shape and internal structure can therefore serve as an effective tool for risk reduction. During the drying of meat products, physicochemical and microstructural changes play a critical role in shaping moisture removal kinetics, structural properties, and overall product quality. Moisture reduction through drying is a key mechanism for limiting microbial growth; however, the effectiveness of this mechanism depends not only on technological conditions (such as temperature and processing time), but also on the internal structure of the product. Recent reviews indicate that drying methods and associated microstructural changes affect drying kinetics, the ability of water to diffuse toward the surface, mass transfer pathways, and, consequently, the safety and quality of meat products (Mediani et al., 2022).

For example, research findings reported by Kabil et al. (2025) demonstrated that different drying techniques (hot-air, infrared, and microwave drying) exert distinct effects on microstructure and dehydration characteristics in meat samples, thereby confirming the importance of considering structural effects within technological processes. In particular, drying temperature and method significantly alter microstructure, shrinkage behaviour, moisture diffusion rates, and post-drying product properties, including sensory attributes.

The dehydration dynamics of meat products are also closely related to sample geometry and size, which directly affect diffusion pathways for water. The application of drying kinetics models based on Fick's law has demonstrated that the three-dimensional geometry of the product, heterogeneity of initial moisture content, and the combination of internal and external diffusion resistances determine the rate and uniformity of moisture removal (Álvarez et al., 2021). This indicates that product-forming parameters – such as shape, thickness, and internal tissue organisation – are important factors governing mass transfer during drying.

In addition, studies by Aksoy et al. (2019) have shown that different drying methods induce distinct changes in the microstructure of the meat matrix, which are reflected in water reabsorption capacity, colour, porosity, and other quality characteristics. For example, the use of ultrasonic-assisted vacuum drying resulted in higher matrix porosity and a more open structure compared to conventional methods, which in turn affected drying kinetics and the properties of the final product.

Drying temperature and duration also influence the dehydration of muscle proteins and fats, leading to changes in sensory attributes. Microstructural modifications induced by drying may affect hardness, texture, and rehydration capacity, which are important not only from the perspective of final product quality but also in terms of product safety (Li et al., 2025). This is because heterogeneous structures may give rise to zones with different levels of water activity and, consequently, varying risks of microbiological stability.

Public interest in improving safety and reducing risks in meat products also stimulates the development of technological approaches that consider product structural characteristics as an integral part of risk management systems. This includes the assessment of the impact of structural and engineering solutions on moisture transport kinetics, physicochemical changes in the protein–fat matrix, as well as final sensory properties and product safety (Mediani et al., 2022). Such approaches are consistent with the principles of multi-barrier control, in which structural parameters become additional resources for risk management, either as alternatives to or in combination with traditional ingredients and technological additives.

Thus, controlling product shape and internal structure represents a promising direction for optimising drying processes and reducing safety-related risks in meat products. This provides a scientific foundation for the further consideration of specific engineering solutions that can be applied to homogenise moisture and water activity profiles and to shorten the duration during which products remain under potentially hazardous conditions. This aspect is particularly important in the development of meat products intended for children and sensitive population groups.

For food products, and meat products in particular, the practical adaptation of safe-by-design implies the following. Risk reduction should not be limited solely to changes in formulation or the introduction of additional barrier ingredients; instead, product geometry, shape, and internal structure should be considered as parameters capable of controlling mass transfer processes, the formation of water activity profiles, and the duration for which the product remains within the "risk window". In HACCP terminology, this effectively represents a shift of part of risk control from "additional measures" to the primary design of the product itself. This approach is consistent with the engineering interpretation of SbD as an iterative process (Sánchez Jiménez et al., 2020), in which solutions that preserve product functionality while reducing health risks are selected and subsequently verified using appropriate indicators (e.g. water activity profiles, microbiological criteria, and sensory properties).

In parallel, the European Union is developing the Safe and Sustainable by Design (SSbD) framework for chemicals and materials, which requires safety considerations to be integrated already at the R&D stage and decision-making to be guided by a "safety + life cycle" perspective (European Commission [EC], 2025). Although SSbD is directly targeted at materials, its emergence signals a broader European trend in which regulatory attention is shifting toward the early "embedding" of safety into design decisions. For food technologies, this provides a meaningful conceptual context and a terminological reference framework as a guiding logic, though not yet as an established sector-specific term.

Thus, within a risk-oriented approach to meat products intended for children and sensitive population groups, safe-by-design can be appropriately interpreted as an applied concept of product and process design. According to this concept (Lelieveld et al., 2014), critical risks – primarily microbiological risks associated with water activity and dehydration non-uniformity – are first identified and subsequently mitigated through engineering decisions related to product shape and structure as well as drying parameters, prior to any "corrective" modification of formulation composition. This provides a scientific basis for moving toward the analysis of specific structural solutions in meat systems that are capable of deliberately shortening diffusion pathways and homogenising internal product conditions during drying.

Several approaches to structural solutions for controlling mass transfer in dried meat products can be distinguished. For dried meat products (including dry-fermented and dry-cured sausages, dried whole-muscle products, jerky, etc.), the key technological challenge is the controlled reduction of moisture content and water activity throughout the entire product volume within an acceptable time frame, without compromising product quality. Syntheses of contemporary research indicate that, alongside drying environment parameters (temperature, relative humidity, air velocity), structural characteristics of the product play a decisive role, as they determine internal mass transfer resistance and the spatial heterogeneity of moisture content and water activity profiles within the raw material (Mediani et al., 2022).

Control of product geometry and characteristic dimensions (thickness/ radius/shape) can be described as follows. In most drying models of meat products, internal mass transfer is represented by a diffusion mechanism (even though the real system may be more complex), and in this case the characteristic diffusion length (e.g. sausage radius or layer thickness) directly determines the rate of moisture equalisation. The shorter the diffusion path, the faster a safe water activity profile is established. From a mathematical standpoint, such systems are frequently approximated using Fickian diffusion models, where characteristic diffusion length becomes a critical determinant of dehydration kinetics (Crank, 1975). Shrinkage phenomena further modify effective diffusion pathways and must be considered in realistic modelling scenarios (Mayor & Sereno, 2004). The practical significance of geometry and deformation/shrinkage during drying is demonstrated by models of dry-fermented sausages that account for real or irregular shapes and shrinkage behaviour (Cascone et al., 2015).

Control of internal microstructure and porosity exhibits specific features. Studies on meat drying processes show that drying conditions shape porosity, density, and microstructure, which in turn affect drying rate and product quality attributes such as texture, rehydration capacity, and hardness. Review studies explicitly emphasise the link between drying processes and porosity and structure, and subsequently their influence on drying kinetics and product properties (Mediani et al., 2022).

In addition, it has been demonstrated (Kim et al., 2022) that pore formation can reduce undesirable shrinkage and excessive hardness in certain dried meat products (e.g. jerky), which is particularly important for the acceptability of products intended for sensitive population groups.

Control of matrix heterogeneity (fat phase content and characteristics of the protein network) leads to the following considerations. Drying occurs within a multicomponent protein–fat matrix, and microstructural changes during dehydration affect both mass transfer and sensory properties. Practical studies on the drying of meat raw materials indicate (Kabil et al., 2025) that different drying regimes significantly alter microstructure and quality indicators (including colour, texture, and oxidation-related parameters). Thus, structural solutions should be evaluated not only in terms of drying rate, but also with respect to quality changes.

However, any structural solution that accelerates moisture removal may potentially alter moisture gradients, shrinkage behaviour, and the formation of a surface layer or crust. This can result in undesirable effects such as the occurrence of locally overdried zones, texture non-uniformity, loss of juiciness, and enhanced oxidative processes. For this reason, contemporary reviews on meat drying dynamics (Álvarez et al., 2021) emphasise the need for a comprehensive analysis that accounts for drying kinetics, internal and external mass transfer resistances, microstructure, and product quality.

A separate methodological aspect concerns the heterogeneity of water activity and the sensitivity to sampling location in dried and fermented meat products. This issue is particularly relevant for any structural innovations (Beňo et al., 2023), as they may modify the spatial water activity profile. Accordingly, control and comparative assessments should be performed using consistent and appropriate sampling protocols (e.g. centre versus periphery of the product, standardised sample preparation).

For products intended for children and sensitive population groups, structural solutions should be selected according to the following set of criteria, which integrate product safety and quality:

1. emphasis on drying kinetics (reduction of the time required to reach the target water activity value) (Álvarez et al., 2021);
2. emphasis on the heterogeneity of moisture content and water activity profiles (reduction of centre-to-periphery gradients and improved reproducibility of results) (Beňo et al., 2023);
3. emphasis on product quality (structure and texture, colour, and oxidation indicators as markers of stability) (Kabil et al., 2025);
4. technological feasibility of product manufacturing (applicability in real production conditions, controllability of process parameters, and absence of new contamination sources in accordance with hygienic design principles) (Mediani et al., 2022).

When formulated in this way, the approach fully complies with risk-oriented logic. This is because it does not introduce an additional barrier without proper justification; instead, product shape and/or internal structure are designed so as to deliberately reduce risk factors – primarily the duration of potentially hazardous internal conditions and the heterogeneity of water activity – while maintaining product quality.

Based on this, the following generalisations of the risk-oriented approach can be made, and directions for further research on meat products intended for children and sensitive consumer groups can be identified.

The analysis of scientific literature indicates that the safety of dried meat products is formed as a result of the interaction of multiple protective barriers, among which water activity, dehydration dynamics, spatial moisture gradients, and structurally determined features of mass transfer within the protein–fat matrix play a key role. This is consistent with the principles of the hurdle technology concept, according to which an increased level of safety can be achieved not only through ingredient-based solutions, but also through the control of process parameters and product properties.

In the context of products intended for children and sensitive population groups, a risk-oriented approach requires particular attention to factors that determine the duration for which a product remains under potentially hazardous conditions, as well as to the heterogeneity of the internal microenvironment. For this reason, the control of water activity and related parameters should be based not only on final values, but also on appropriately selected sampling methodologies and the assessment of internal moisture profiles. This is essential for the objective comparison of technological solutions aimed at intensifying drying processes.

Conclusions

The adaptation of the safe-by-design logic to food technologies can be regarded as a practical extension of the risk-oriented approach. In this context, risk reduction is achieved by designing technological processes and product characteristics in such a way as to minimise the occurrence of hazardous scenarios (e.g. prolonged zones of elevated water activity) and to improve the reproducibility of safety indicators. In the food sector, closely related concepts include hygienic design of equipment and risk-oriented process design, in which engineering solutions are considered integral components of food safety management systems rather than merely technical support for production.

Based on the above considerations, the following research directions appear promising for dried meat products intended for children and sensitive population groups:

- development of methodologies for comparative assessment of technological solutions based on water activity profiles and microbiological stability indicators;
- investigation of the effects of product shape and internal structure on drying kinetics and product quality;
- identification of technologically justified approaches to reducing dependence on preservative additives through the controlled enhancement of other food safety barriers.

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Заява про доступність даних / Data Availability Statement

Це дослідження не генерувало нових експериментальних даних і базується на аналізі та синтезі наукових публікацій, нормативних документів та відкритих джерел. Усі використані дані та джерела інформації представлені безпосередньо в тексті статті та у списку літератури / This study did not generate new experimental data and is based on the analysis and synthesis of scientific publications, regulatory documents, and open sources. All data and information sources used are presented directly in the text of the article and in the reference list.

Заява інституційної ревізійної ради / Institutional Review Board Statement

Не застосовується / Not applicable.

Заява про інформовану згоду / Informed Consent Statement

Не застосовується / Not applicable.

Конфлікт інтересів / Conflict of interest

Автори заявляють про відсутність конфлікту інтересів. Жодне фінансування, спонсорство чи інший вплив з боку зовнішніх організацій не вплинули на проведення дослідження, інтерпретацію результатів або підготовку рукопису / The authors declare no conflict of interest. No funding, sponsorship, or other influence from external organisations affected the conduct of the study, the interpretation of results, or the preparation of the manuscript.

Декларація про генеративний штучний інтелект і технології на основі штучного інтелекту в процесі написання / Declaration on Generative Artificial Intelligence and AI-enabled Technologies in the Writing Process

У цьому дослідженні не використовувався генеративний штучний інтелект або технології штучного інтелекту для збору, аналізу чи інтерпретації даних / This study did not use generative artificial intelligence or AI-enabled technologies to collect, analyze, or interpret data.

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