https://doi.org/10.31891/2307-5732-2026-365-20
УДК 664.9:534.6

BATRACHENKO OLEXANDR
Cherkassy State Technological University
https://orcid.org/0000-0001-8920-0743
e-mail: o.batrachenko@chdtu.edu.ua
DOROSHKO DENYS
Cherkassy State Technological University
https://orcid.org/0009-0007-1477-3660
e-mail: d.r.doroshko.asp24@chdtu.edu.ua

LIPID PHASE OF DRY SAUSAGES AS A FACTOR IN THE FORMATION OF TRANSPORT BARRIERS DURING DRYING

Drying is a decisive stage in the production technology of dry sausages, as it determines their physicochemical, structural–mechanical, sensory, and microbiological characteristics. In classical technological approaches, the control of the drying process is focused primarily on external environmental parameters (temperature, relative humidity, air flow velocity), while the internal structure of the sausage batter is considered a result of random formation during raw material comminution and mixing. In particular, the role of the lipid phase remains insufficiently studied and is traditionally assessed only in terms of fat content and average particle size. In this work, a conceptually new interpretation of the lipid phase of dry sausages is proposed, considering it as a system-forming element of the internal transport architecture of the product. It is substantiated that fat performs the function of a drying multibarrier, combining diffusive, thermal, and geometric resistance to mass and heat transfer. It is demonstrated that the decisive factor governing dehydration kinetics is not only the fat content, but primarily the topology of its spatial distribution within the meat matrix. Based on the analysis of literature data and the generalization of transport properties of the constituent phases, it is established that the moisture diffusion coefficient in the lipid phase is 2–3 orders of magnitude lower than that in muscle tissue, while the thermal conductivity of fat is 2–2.5 times lower. This leads to an increase in the effective diffusion path length, higher mass transfer tortuosity, and the formation of local zones with reduced drying rates. As a result, heterogeneous moisture and temperature fields develop within the sausage cross-section, causing nonlinear drying behavior and increased variability in the quality of the final product. The study formulates a system of scientific hypotheses describing the relationship between lipid phase topology, the multibarrier drying effect, and the effective intensity of moisture diffusion. A transition is proposed from empirical regulation of drying regimes to an engineering-based approach founded on the purposeful design of the internal transport architecture of dry sausages by controlling the shape, size, and spatial organization of lipid inclusions. The obtained results provide a scientific basis for the further development of dry sausage drying technologies with predictable kinetic and quality characteristics.

Keywords: *dry sausages; lipid phase; transport architecture; mass transfer; tortuosity; moisture diffusion.*

БАТРАЧЕНКО ОЛЕКСАНДР, ДОРОШКО ДЕНИС
Черкаський державний технологічний університет

ЖИРОВА ФАЗА СУХИХ КОВБАС ЯК ФАКТОР ФОРМУВАННЯ ТРАНСПОРТНИХ БАР'ЄРІВ ПРИ СУШІННІ

Сушіння є визначальним етапом технології виробництва сухих ковбас, що формує їх фізико-хімічні, структурно-механічні, сенсорні та мікробіологічні характеристики. У класичних технологічних підходах керування процесом сушіння зосереджується переважно на зовнішніх параметрах середовища (температура, відносна вологість, швидкість повітряного потоку), тоді як внутрішня структура ковбасного батона вважається результатом випадкового формування під час подрібнення і змішування сировини. Особливо обмежено вивчено роль жирової фази, яку традиційно оцінюють лише за масовою часткою та середнім розміром включень. У даній роботі запропоновано концептуально нове трактування жирової фази сухих ковбас як системоутворюючого елемента внутрішньої транспортної архітектури продукту. Обґрунтовано, що жир виконує функцію мультибар'єра сушіння, поєднуючи дифузійний, тепловий та геометричний опір масо- і теплоперенесенню. Показано, що визначальним фактором кінетики зневоднення є не лише кількість жиру, а передусім топологія його просторового розподілу в м'ясній матриці. На основі аналізу літературних даних та узагальнення транспортних властивостей фаз встановлено, що коефіцієнт дифузії вологи в жировій фазі є на 2–3 порядки нижчим порівняно з м'язовою тканиною, тоді як теплопровідність жиру в 2–2,5 рази менша. Це призводить до зростання ефективної довжини дифузійних шляхів, підвищення тортуозності масоперенесення та формування локальних зон уповільненого сушіння. У результаті в об'ємі ковбасного батона виникають неоднорідні поля вологості та температури, що зумовлюють нелінійність процесу сушіння і підвищену варіабельність якості готової продукції. У роботі сформульовано систему наукових гіпотез, які описують взаємозв'язок між топологією жирової фази, мультибар'єрним ефектом сушіння та ефективною інтенсивністю дифузії вологи. Запропоновано перехід від емпіричного регулювання режимів сушіння до інженерного підходу, заснованого на цілеспрямованому проєктуванні внутрішньої транспортної архітектури сухих ковбас шляхом керування формою, розмірами та просторовою організацією жирових включень. Отримані результати формують наукову основу для подальшого розвитку технологій сушіння сухих ковбас із прогнозованими кінетичними та якісними характеристиками.

Ключові слова: *сухі ковбаси; жирова фаза; транспортна архітектура; масоперенесення; тортуозність; дифузія вологи.*

Стаття надійшла до редакції / Received 10.02.2026
Прийнята до друку / Accepted 11.03.2026
Опубліковано / Published 28.05.2026

Problem Statement in a General Form and Its Connection with Important Scientific and Practical Tasks

Drying is one of the key stages in the production of dry fermented sausages, determining not only the development of consumer properties of the product but also its microbiological stability and safety. Despite the substantial body of scientific research devoted to optimizing drying regimes, sausage manufacturing practice still faces persistent challenges associated with non-uniform dehydration, surface hardening (case hardening) of sausage batons, and the necessity to apply elevated safety margins in technological parameters.

Within the classical technological paradigm of dry sausage production, primary attention is focused on regulating external process factors, such as temperature, relative humidity, air velocity, and processing time. Meanwhile, the internal structure of the sausage baton is generally regarded as a secondary factor, statistically formed during mincing and mixing, and not requiring purposeful control.

A particular role within this structure is attributed to the lipid phase (backfat), whose influence is traditionally assessed mainly through its mass fraction and the size of lipid inclusions. Although such an approach is convenient from the standpoint of formulation control, it does not fully explain the observed variability in drying intensity, even within a single production batch.

In this context, it becomes necessary to reconsider the role of the lipid phase (backfat) not as a passive ingredient but as an active structural and functional element that forms internal transport barriers and determines the efficiency of coupled mass and heat transfer processes during the drying of dry fermented sausages.

Analysis of Research and Publications

The drying of dry and fermented sausages is considered in contemporary research as a complex, multifactorial process involving coupled mass and heat transfer, structural transformations of the protein–lipid matrix, and microbiological changes within the product. Comprehensive reviews indicate that dehydration kinetics are governed not only by external drying parameters (temperature, relative humidity, air velocity), but also by intrinsic product properties, particularly its structural organization and phase composition [1].

A number of studies confirm that the geometric parameters of the sausage baton (diameter, shape) significantly influence drying and ripening processes. As the diameter increases, the effective diffusion path length for moisture transport increases, leading to more pronounced moisture and water activity gradients and, consequently, to product heterogeneity [2]. Similar conclusions have been reported in experimental investigations of sausage drying kinetics, demonstrating that shrinkage and internal structural changes represent critical factors complicating uniform dehydration [3].

Water activity (aw) is widely regarded as a key integral indicator of safety in dry fermented sausages. Investigations of various traditional dry sausages have shown that even when the average water activity values comply with regulatory requirements, localized zones with elevated moisture content may persist within the product, creating risks of microbiological instability [4]. This highlights the necessity of analyzing not only mean values, but also the spatial distribution of water-related parameters within the product matrix.

The influence of drying conditions on the quality of dry sausages has been extensively examined in studies focusing on the regulation of relative humidity. It has been demonstrated that excessively intensive drying promotes the formation of a surface crust (case hardening), which restricts further mass transfer from the central regions of the sausage baton [5]. In this context, internal structural barriers may play a role that is no less significant than that of external process conditions.

A number of investigations have also addressed microbiological and physicochemical changes occurring during the ripening of dry sausages. It has been shown that the rate of dehydration affects microbial dynamics and the accumulation of fermentation metabolites [6, 7]. However, in most of these studies, the internal structure of the product is treated primarily as a given condition rather than as a controllable technological parameter.

The lipid phase is traditionally described in the literature primarily from the standpoint of formulation composition and its influence on sensory properties. Studies addressing the effects of different lipid types and ripening rates demonstrate that the type and morphology of the lipid phase significantly affect sausage texture and microbiological characteristics [8]. However, the role of lipids as a factor governing mass and heat transfer is rarely analyzed directly.

Investigations focused on reducing nitrite and salt content in dry sausages indicate that delayed drying and non-uniform dehydration may complicate the assurance of product safety [9, 10]. This indirectly confirms that internal mass transfer barriers play an important role in shaping the final characteristics of the product.

Certain authors have employed porous or heterogeneous models to describe sausage ripening processes, considering the product as a non-uniform medium [11]. Nevertheless, such approaches are predominantly modeling-oriented and are seldom linked to specific technological methods for deliberately forming the internal structure.

Classical works on dry meat technology emphasize the decisive role of diffusion processes in determining sausage quality and stability; however, they typically treat product structure as a consequence of formulation and mechanical processing rather than as an object of purposeful engineering design [12, 13].

An analysis of contemporary publications reveals the following. The drying of dry sausages is predominantly examined from the perspective of external technological regimes and overall process kinetics. While baton geometry and drying conditions are recognized as important factors, the spatial organization of the lipid phase is rarely analyzed as an independent factor affecting mass and heat transfer. The influence of lipids in dry sausages is mainly studied in terms of formulation, texture, and sensory properties, whereas their role as a multi-barrier system for moisture and heat remains insufficiently elucidated. This creates a scientific niche for developing a concept of the lipid phase as an active element of the internal transport architecture of dry fermented sausages.

Formulation of the Objectives of the Study

The aim of this study is to provide a scientific substantiation of the role of the lipid phase in dry fermented sausages as a structural and functional element of the internal transport architecture, which generates a multi-barrier resistance to mass and heat transfer during drying and determines dehydration kinetics, spatial moisture heterogeneity, and the technological controllability of the ripening process.

The objectives of the study are as follows:

- to analyze current scientific concepts regarding the mechanisms of mass and heat transfer in dry fermented sausages, taking into account the heterogeneous structure of protein–lipid systems;
- to substantiate the concept that the lipid phase acts as a transport barrier within the multiphase protein–lipid matrix of dry sausages;
- to compare the transport characteristics of the muscle and lipid phases (effective diffusivity, thermal conductivity) and evaluate their influence on the formation of internal moisture and temperature gradients;
- to formulate hypotheses concerning the impact of the topology and morphology of lipid inclusions on drying kinetics and the stability of quality attributes in dry fermented sausages;
- to identify the scientific premises for controlling the drying of dry sausages through the purposeful formation of a lipid-based transport architecture.

Main Body of the Study

In conventional dry sausage technology, the lipid phase is primarily regarded as a formulation component responsible for the sensory attributes of the product—flavor, juiciness, aroma, and texture. Its spatial distribution within the sausage baton is typically considered a random outcome of mincing, mixing, and stuffing processes.

However, from the standpoint of mass and heat transfer, the lipid phase represents a structurally significant element that shapes the internal transport architecture of the product. Lipids differ substantially from muscle tissue in terms of hydrophilicity, thermal conductivity, porosity, and the ability to form capillary pathways. Consequently, the lipid phase inevitably affects the formation of moisture and heat fluxes during drying.

Based on this reasoning, the present study advances the hypothesis that the lipid phase in dry fermented sausages functions as a transport barrier, and that the nature and magnitude of this barrier depend not only on the lipid mass fraction, but primarily on its topology—that is, its spatial organization within the baton volume.

The principal mechanism of dehydration in dry sausages is the diffusive transfer of moisture from the internal regions of the sausage baton toward the surface, followed by evaporation. After comminution, muscle tissue forms a capillary–porous structure capable of relatively efficient moisture transport. In contrast, the lipid phase is practically impermeable to water.

When lipid inclusions are present within the sausage matrix, the diffusion path of moisture becomes more tortuous, leading to an increase in transport path tortuosity. The greater the extent of lipid layers, or the closer they are located to the baton surface, the more pronounced the diffusion resistance becomes.

Thus, the lipid phase forms a diffusion barrier that:

- increases the effective migration path length of moisture;
- promotes the formation of internal moisture gradients;
- delays the attainment of equilibrium water activity.

This effect may manifest even at relatively low lipid mass fractions if the lipid phase is organized in the form of continuous or semi-continuous regions that interrupt the capillary network of the muscle matrix.

In addition to diffusion resistance, the lipid phase also affects heat transfer during drying. The thermal conductivity of lipids is lower than that of dehydrated muscle tissue, resulting in localized thermal heterogeneity within the baton.

As demonstrated by the data presented in Table 1, the muscle and lipid phases of dry fermented sausages differ fundamentally in their transport properties, which determines their distinct functional roles in mass and heat transfer processes during drying.

The muscle phase, which represents a protein–water porous matrix, is characterized by relatively high values of effective moisture diffusivity ($D_e \approx 0.5–3.0 \times 10^{-10}$ m²/s). This enables it to function as the primary mass transfer pathway through which moisture migrates from the internal regions of the product toward the surface. In addition, the thermal conductivity of the muscle phase ($\lambda \approx 0.45–0.55$ W/(m·K)) promotes a relatively uniform heat distribution within the baton volume during the initial stages of drying.

Table 1

Comparison of the Properties of the Muscle and Lipid Phases in Dry Fermented Sausages

Parameter	Muscle Phase (Protein–Water Matrix)	Lipid Phase (Backfat)	Comment
Effective moisture diffusivity, D_e (m²/s)	$(0.5–3.0) \times 10^{-10}$	$10^{-12} – 10^{-13}$	The lipid phase reduces mass transfer by 2–3 orders of magnitude, forming diffusion discontinuities
Relative diffusion capacity	1	0.001–0.01	The lipid phase is practically diffusion-inactive
Thermal conductivity, λ (W/m·K)	0.45–0.55	0.18–0.25	Lipids conduct heat 2–2.5 times less effectively than the muscle phase
Thermal role during drying	Active heat conductor	Thermal insulator	The lipid phase promotes local surface overheating and case hardening
Influence on transport path tortuosity	Low to moderate	High (under non-uniform distribution)	The lipid phase increases the tortuosity of mass transfer pathways
Functional role in internal architecture	Load-bearing transport matrix	Multi-barrier phase	The lipid phase acts simultaneously as a diffusion and thermal barrier
Implications for drying	Stable dehydration	Retardation, heterogeneity	Formation of moisture retention zones and safety-related risks

In contrast, the lipid phase (backfat) exhibits extremely low diffusion permeability. The effective moisture diffusivity of lipid tissue is on the order of 10^{-12}–10^{-13} m²/s, i.e., 2–3 orders of magnitude lower than that of the muscle matrix. This effectively means that the lipid phase is nearly diffusion-inactive with respect to moisture and acts as a local barrier to mass transfer.

Beyond its diffusive inertness, the lipid phase also possesses reduced thermal conductivity ($\lambda \approx 0.18$–0.25 W/(m·K)), which determines its function as a thermal insulator. When lipid inclusions are located in the near-surface layers of the sausage baton, they promote localized heat accumulation, accelerated drying of the outer zones, and the formation of a dense surface crust. This crust further increases resistance to mass transfer, thereby intensifying dehydration non-uniformity.

During the drying of dry fermented sausages, the muscle matrix undergoes shrinkage, whereas the lipid phase experiences minimal comparable volumetric changes. This mismatch leads to the development of internal stresses and localized structural deformation within the product.

At the interfaces between the muscle and lipid phases, microcracks, compacted layers, and regions of reduced porosity may form. Such structural transformations further alter the configuration of capillary pathways and may either locally facilitate or hinder mass transfer. However, in aggregate, this mechanism reinforces the structural–mechanical barrier superimposed upon the diffusive and thermal barriers.

Importantly, the influence of the lipid phase on drying is not determined solely by its absolute content. The decisive factor is the topology of its spatial distribution within the product volume (Fig. 1). Non-uniformly distributed or elongated lipid inclusions substantially increase the tortuosity of transport pathways within the muscle matrix, forcing moisture to migrate along bypass trajectories with elevated resistance. Under such conditions, even at identical average moisture contents, localized moisture retention zones may develop, adversely affecting drying stability and the microbiological safety of the product.

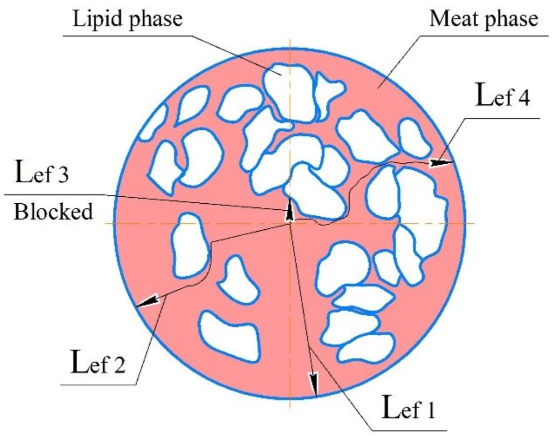

Fig. 1. Schematic representation of a cross-section of a dry fermented sausage with a heterogeneous lipid phase forming local transport barriers that increase the effective mass transfer path length (L_{ef}, tortuosity) and reduce the intensity of moisture diffusion during drying ($L_{ef1} < L_{ef2} < L_{ef4} < L_{ef3}$ (blocked))

In summary, the lipid phase of dry fermented sausages can be regarded as a multi-barrier element simultaneously affecting several key processes:

- Diffusion barrier — restriction and increased tortuosity of moisture migration pathways;
- Thermal barrier — reduction in heating uniformity and stimulation of surface crust formation;
- Structural barrier — deformation of the transport architecture due to unequal shrinkage of the constituent phases.

The interaction of these barriers explains why, within a single production batch of dry fermented sausages, substantial differences may be observed in drying duration, dehydration uniformity, and microbiological stability, even under identical external technological regimes.

Since the lipid phase in dry sausages performs a multi-barrier function, it may be considered not merely as a formulation ingredient, but as a key structural component of the product’s internal transport architecture. Purposeful control of the spatial topology of the lipid phase opens the possibility of targeted regulation of drying intensity, dehydration uniformity, and the associated quality and safety parameters of dry fermented sausages.

Based on the above considerations, the following scientific hypotheses are formulated:

1) The efficiency of drying in dry fermented sausages is determined not only by the total lipid phase content and external drying regimes, but primarily by the topology of the spatial distribution of the lipid phase in the cross-section of the baton, which forms the internal transport architecture of the product and governs the intensity of coupled mass and heat transfer processes;

2) Disruption of the continuity of the muscle phase by lipid inclusions in critical zones of the transport architecture increases the tortuosity of moisture diffusion pathways and reduces the effective area available for mass transfer;

3) Localization of the lipid phase near the surface of the baton creates additional thermal resistance, reducing heat flux into the muscle matrix and promoting temperature field heterogeneity during drying;

4) The synergy between mass transfer and thermal barriers leads to accelerated formation of a dense surface layer, which acts as a secondary diffusion barrier and further retards drying;

5) Even minor changes in the topology of the lipid phase may result in nonlinear variations in drying rate due to positive feedback mechanisms between mass transfer, heat transfer, and surface structural evolution.

The proposed concept establishes the prerequisites for transitioning from empirical formulation adjustments to engineering control of the internal transport architecture of dry fermented sausages through purposeful formation of lipid phase topology. This approach enables drying intensification, improved quality uniformity, and reduced technological risks without altering the fundamental principles of traditional sausage technology.

Conclusions and Prospects for Further Research

It has been demonstrated that the lipid phase in dry fermented sausages should be regarded not only as a formulation component but as a structurally significant element that determines the internal transport architecture of the product and substantially influences the drying process. It has been substantiated that the impact of the lipid phase on moisture mass transfer is governed not so much by its quantitative content as by its spatial organization, which determines the tortuosity and discontinuity of diffusion pathways within the muscle matrix.

It has been established that the lipid phase may act as a thermal barrier, contributing to non-uniform heating of the sausage baton and to the accelerated formation of a surface crust that further restricts mass transfer from internal regions. It has also been shown that the unequal deformation of the muscle and lipid phases during drying leads to structural–mechanical transformations that alter the configuration of transport pathways and enhance internal heterogeneity within the product.

A concept of the lipid phase in dry fermented sausages as a multi-barrier element in drying has been proposed, integrating diffusion, thermal, and structural mechanisms that limit mass transfer processes. It has been substantiated that uncontrolled lipid phase topology represents one of the key sources of quality variability within a single production batch of dry sausages, even under stable external technological regimes. It has been determined that purposeful formation of lipid phase topology opens prospects for engineering control of the drying process in dry fermented sausages in order to enhance drying intensity, improve uniformity, and increase microbiological safety.

Future research directions may include the experimental characterization of lipid phase topology in dry fermented sausages of the most popular commercial brands available on the market, with the aim of identifying typical architectural patterns and assessing their relationship with drying performance and product stability.

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