№ 4 (131) / 2025
Vol. 131, № 4 / 2025
Техніка, енергетика, транспорт АПК

UDC 631.3.003.13:66.061.34
DOI: 10.37128/2520-6168-2025-4-6

PHYSICAL PRINCIPLES AND CLASSIFICATION OF FEED MATERIAL MIXING PROCESSES

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The mixing processes of multicomponent feed materials are characterized by a complex physical nature resulting from the combination of various mechanisms of transport, deformation, and structural rearrangement of the material medium. In real feed preparation technologies, granular, cohesive, fibrous, and viscoplastic components interact simultaneously, which leads to the formation of different material flow regimes and complicates the achievement of stable spatial homogeneity. Existing classifications of mixing processes are mainly oriented toward the design features of equipment or specific groups of materials and therefore do not provide a generalized, physically substantiated description of the process.

The aim of this study is to develop an integrated, physically oriented classification of feed material mixing processes that is invariant with respect to the structural type of the mixing apparatus. The methodological basis of the research is a system-level analysis of contemporary theoretical and experimental studies in mixing physics, the mechanics of granular and cohesive media, and the rheology of viscoplastic materials.

The basic physical mechanisms of mixing are systematized, and a set of physical and structural–topological descriptors is introduced, enabling a generalized description of the process evolution regardless of its hardware implementation. Based on the analysis of the manifestations of these descriptors, the dominant process regimes are identified as generalized physical scenarios of material transport and deformation. An integrated classification of feed material mixing processes is proposed, in which the process class is determined by the combination of the structural–mechanical nature of the medium and the dominant regime, taking into account demixing phenomena.

The obtained results provide a theoretical basis for further quantitative analysis of mixing processes, optimization of feed mixer operating modes, and the substantiated selection of their design and technological parameters.

Key words: *multicomponent mixtures, physical interaction, transport mechanisms, dominant regimes, structural organization, demixing, segregation, engineering typology, mixing apparatuses.*

Eq. 6. Fig. 3. Table 2. Ref. 26.

1. Problem formulation

The process of mixing feed materials in multicomponent mixtures belongs to complex physico-mechanical phenomena, as it involves the interaction of particles with different types of interparticle bonds, various modes of deformation, and distinct kinematic patterns of motion. Within a single technological cycle, the mixing chamber may contain components exhibiting frictional granular, cohesive–adhesive, fibrous, or viscoplastic properties. Such pronounced heterogeneity of physical characteristics leads to the emergence of different material transport regimes, necessitates the formation of localized shear zones and structural breakdown, and effectively precludes the use of a single universal mixing mechanism for all types of components.

An analysis of existing scientific approaches shows that most current classifications of mixing processes are primarily oriented toward the design features of mixing equipment or the characteristics of specific groups of materials. At the same time, the scientific literature practically lacks a generalized classification based on the physical principles of motion, interaction, and deformation of feed components that is independent of the specific type of mixer. The absence of such a physically oriented classification model complicates the substantiated selection of rational technological regimes and design solutions for the efficient mixing of multicomponent feed mixtures.

Article received 24.10.2025. Article accepted 08.12.2025. Article published 25.12.2025.

In this regard, there arises a need to establish a fundamental basis for the analysis of mixing processes that integrates the physical mechanisms of material transport and deformation with the characteristics of different types of feed components and serves as a theoretical foundation for further design, rheological, and technological studies.

2. Analysis of recent research and publications

Modern understanding of mixing processes has been developed primarily within a general industrial context. In the fundamental work [1], the basic mixing mechanisms – convective transport, diffusive mixing, and shear deformation – are identified. These mechanisms are considered a universal basis for the analysis of various types of equipment (paddle, ribbon, drum, planetary, high-shear mixers, etc.) and are applied mainly to granular, suspension, viscous, and viscoplastic media. At the same time, within this approach the material is usually described in a generalized manner, without a detailed typology based on frictional–cohesive, fibrous, or viscoplastic properties, which is critically important for multicomponent feed mixtures.

The classical review by Ottino and Khakhar [2] deepens the physical description of mixing and segregation processes in granular materials, focusing on the kinematic regimes of particle motion, the formation of localized shear zones, and the interaction between convective mixing and segregation mechanisms that may lead to stratification. It is shown that even in apparatuses with simple geometry (rotating drums, blenders), the combination of convective flows, localized shear zones, and segregation mechanisms forms complex spatial structures of material motion that cannot be adequately described solely by integral statistical mixing criteria. For feed mixtures, this implies that differences in particle size, density, and shape generally promote selective transport of components and the formation of local stratification.

The development of numerical methods, primarily the Discrete Element Method (DEM), has enabled a transition from the description of averaged characteristics to the analysis of mixing micromechanics. The review by Marigo [3] summarizes the application of DEM to industrial processes involving bulk materials, including mixing, conveying, and storage. The author emphasizes that DEM makes it possible to identify local stagnant zones, active mixing layers, and flow structures, thereby linking equipment geometry, motion regimes, and particle properties with the quality of homogenization. Detailed investigations of particle motion in paddle mixers, such as [4], show that even for geometrically simple paddle mixers the combination of cascading, shear, and circulation regimes strongly depends on blade geometry, fill level, and the frictional properties of the material.

For viscoplastic and structurally complex media, which include many feed mixtures with high moisture content and a significant fraction of organic matter, rheological properties are of decisive importance. The review by Bonn et al. [5] systematizes the behavior of yield-stress materials and demonstrates that the transition from a quasi-solid state to flow occurs only after a critical level of shear stress is reached. In the context of mixing, this implies the need to form zones with sufficient shear intensity within the apparatus; otherwise, large volumes of material remain in a “passive” state. Such behavior is particularly characteristic of wet TMR rations, silage masses, and viscoplastic feed components.

In the field of dairy cattle feeding, mixing is considered a key stage in the formation of total mixed rations (TMR), as it determines nutrient availability and ration stability. In a 100-year review, Schingoethe [6] traced the evolution of TMR systems and noted that feed mixture uniformity is one of the fundamental factors ensuring uniform intake and stable productivity of cows. Experimental studies by Moallem and Lifshitz [7] confirm this relationship, showing that the design and kinematic parameters of mixers (machine type, auger configuration and rotational speed, loading conditions) directly affect dosing accuracy and TMR homogeneity, which in turn influences milk yield in high-producing cows. The study by Buckmaster et al. [8], which employed tracer components and statistical analysis of the coefficient of variation, provided a reliable basis for the quantitative assessment of TMR uniformity and represented an important step toward the standardization of methods for evaluating mixing quality in feed mixers.

At the level of specific machines and technological schemes, Vegricht et al. [9] performed a parametric analysis of eight types of TMR mixing–feeding wagons, establishing the influence of fill level, mixing element design, and cycle duration on mixture homogeneity, uniformity of distribution along the feed bunk, energy consumption, and productivity. The results showed that mixtures with a high proportion of hay are characterized by significantly lower homogeneity due to their fibrous structure and tendency to form bridges and clumps. Subsequent studies [10] focused not so much on mixing kinematics as on methods for assessing uniformity, including the use of visual sensor systems (RGB cameras) and statistical indicators for operational quality control of feed mixtures under production conditions.

A separate research direction concerns the combination of DEM modeling and experiments for specialized mixers designed specifically for feed materials. In the work by Cao et al. [11], DEM was used to optimize the parameters of a vertical screw mixer for TMR (screw pitch, bottom inclination angle, rotational speed, and housing wall angle), with the uniformity of particle distribution of different fractions chosen as the efficiency criterion. It was shown that modifying the geometric parameters of the working element makes it possible to significantly reduce stagnant zones and improve mixture homogeneity without a substantial increase in energy consumption. Similar results are reported in a number of review studies on the application of DEM to granular mixing [3, 12], which emphasize the importance of correctly accounting for the frictional, cohesive, and contact properties of particles.

In the work by Lee and Hwang [14], a comparative analysis of the mixing efficiency of fine powder particles in different types of mixers was conducted using quantitative homogeneity indices and visualization-based analysis methods. The obtained results may be partially relevant for evaluating the behavior of fine fractions in multicomponent feed mixtures. The authors found that for cohesive fine materials, localized shear regimes, circulation loops, and the nature of contact interactions between particles govern mixing behavior, whereas integral homogeneity criteria do not represent the actual spatial structure of flows. These findings are consistent with classical concepts of the interaction between convective and segregation mechanisms in granular systems [2] and highlight the importance of a physically oriented approach to the analysis of mixing processes.

For agricultural practice, not only mixing mechanisms but also the energy aspects of technological chains are of fundamental importance. In the monograph [13], energy-efficient technologies for feed preparation and processing are systematically analyzed, and the relationship between feed material properties, technological regimes of size reduction and mixing, and the specific energy consumption of machine–technological systems is identified. Although mixing is presented in [13] mainly as a stage of the overall technology, the authors note that the significant variability of the physical and mechanical properties of components requires a differentiated selection of equipment and technological regimes.

Generalization of the analyzed studies makes it possible to formulate several important points. First, in fundamental works on mixing theory [1–3, 5, 12], the primary focus is on particle motion and flow mechanisms (convection, diffusion, shear, segregation, and localized flow zones in yield-stress materials); however, these approaches do not account for the specificity of feed or other applied multicomponent systems. Second, in studies devoted to TMR mixing systems [6–11, 13], attention is mainly focused on mixer design parameters, loading conditions, dosing accuracy, and integral homogeneity indicators, whereas the physical typology of mixing processes (for granular, cohesive, fibrous, and viscoplastic feeds) remains unformalized. Third, despite the active use of DEM modeling, existing studies predominantly address granular and weakly cohesive materials and do not propose a coherent classification of mixing regimes for complex multicomponent feed systems.

Thus, existing studies provide a fairly deep understanding of individual aspects of the mixing process, including the mechanics of granular and viscoplastic media, the operating features of specific types of mixers, and methods for assessing the uniformity of TMR-type rations. At the same time, there is still a lack of an integrated, physically oriented classification of feed material mixing processes that would systematically combine:

- material types (granular, cohesive/cohesive–adhesive, fibrous, and viscoplastic);
- dominant mechanisms of material transport and deformation;
- characteristic mixing zones and regimes in apparatuses of different types.

Therefore, the identified scientific gap requires a comprehensive, physically substantiated generalization, the development of which forms the basis of the present study.

3. The purpose of the article

The aim of the article is to develop an integrated, physically oriented classification of feed material mixing processes that systematically accounts for their physicomechanical and rheological properties, mechanisms of material transport and deformation, and characteristic flow regimes in mixing apparatuses of different types.

To achieve this aim, the following objectives are addressed:

- to systematize the physical mechanisms of mixing inherent to different types of feed materials (granular, cohesive, fibrous, and viscoplastic) based on an analysis of contemporary theoretical and experimental studies;

- to define a system of physical and structural–topological descriptors that enables a generalized and invariant description of feed material behavior during mixing, independent of the specific mechanism and structural type of the apparatus;
- to identify the dominant regimes of feed material mixing processes as generalized physical scenarios of material transport and deformation (convective, shear, diffusive, segregation-dominated, and localized flow regimes) and to establish their qualitative relationship with the properties of the medium and the characteristic manifestations of physical and structural–topological descriptors;
- to develop a physically substantiated integrated classification of feed material mixing processes as engineering objects, in which the process type is determined by the combination of the structural–mechanical nature of the material medium and the dominant process regime (homogenizing or demixing), regardless of the structural type of the mixing apparatus.

4. Results and discussion

The research methodology is based on a systems approach to the analysis of mixing processes of multicomponent feed materials, which are characterized by a wide variability of physicomechanical and rheological properties. In this study, mixing is treated as a complex physical process that involves interactions between particles of different nature, the formation of localized shear zones, convective flows, segregation structures, and regions of localized flow. Such an approach makes it possible to abstract from the design features of specific mixing apparatuses and to focus on the universal mechanisms that govern material behavior during mixing.

The typologization of feed materials, required for the subsequent identification of characteristic regimes of their transport and deformation, was carried out taking into account the author's previous results obtained in studies of the rheological properties of multicomponent feed mixtures [15, 16]. Accordingly, the classification basis–distinguishing granular, cohesive, fibrous, and viscoplastic materials–is not reconsidered in this article but is used as an initial conceptual framework for analyzing mixing mechanisms. In this work, material types are considered exclusively from the standpoint of their ability to generate specific motion regimes that determine the characteristic features of the mixing process.

The analytical part of the study involved a critical review and systematization of contemporary theoretical works on the mechanics of granular and cohesive media, mixing physics, and the rheology of viscoplastic materials, as well as studies devoted to the behavior of fibrous structures in shear and convective flows. Particular attention was paid to works describing segregation mechanisms, localized flow, agglomerate formation, the breakdown of structured bonds, and nonlinear flow regimes in materials of different physical nature. A comparative analysis of these sources made it possible to identify common regularities and fundamental differences among the mechanisms inherent to different classes of materials.

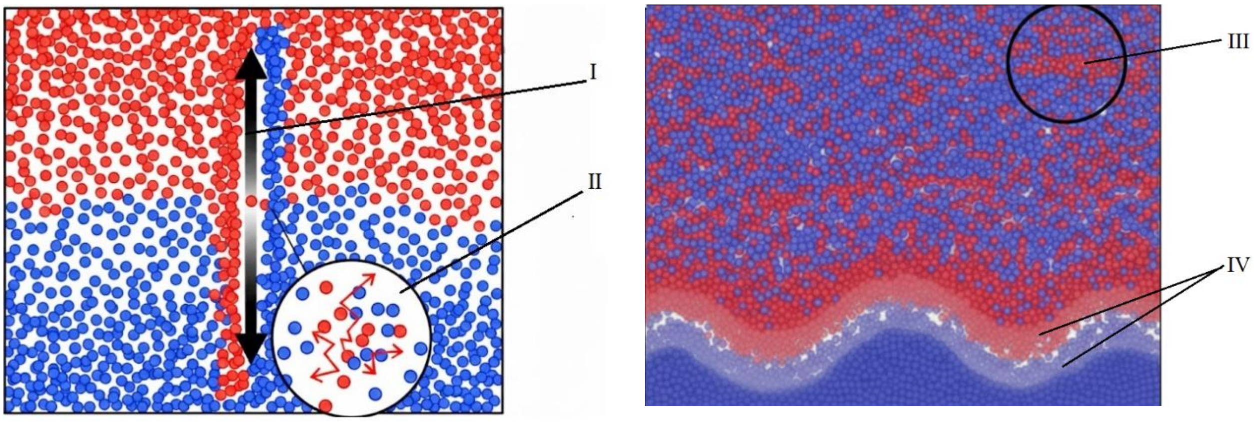
The development of the mixing process classification was carried out by identifying the fundamental physical mechanisms of material transport, deformation, and structural transformation that govern the process regardless of the structural implementation of the mixing apparatus. Within the scope of this study, the basic mixing mechanisms include convective transport of material macro-volumes, shear-induced deformation, collisional (random) diffusion, and the destruction of interparticle structures (agglomerates, clusters, and fibrous formations). Segregation processes are considered separately as demixing phenomena that accompany mixing and may lead to the formation of stable spatial heterogeneity of components. Localized flow is interpreted not as an independent mechanism, but as a characteristic mode of shear deformation realization in threshold (viscoplastic) media. For each of the identified mechanisms, their typical manifestations in materials of different physical nature were determined, ensuring the establishment of correspondence between the properties of feed components and the dominant mixing regime.

The application of a structural–classification approach made it possible to construct a universal classification model in which the physical properties of the material are regarded as the key determining factors of the mixing regime. In contrast to design-oriented classifications, the proposed approach eliminates dependence on the specific type of mixer and can be applied to paddle, ribbon, drum, V-shaped, screw, and other apparatuses that implement physically similar motion mechanisms. Such universality is a necessary condition for the development of fundamental scientific foundations of mixing processes.

The physical essence of the mixing process in multicomponent feed mixtures should be regarded as the result of the interaction of several physically heterogeneous mechanisms of material transport and redistribution, the nature of which is determined by component properties and deformation conditions within the working volume. In classical mixing theory, the process is conventionally described as a combination of convective transport (I) of material macro-volumes and shear-induced (II) microscopic particle displacements

(Fig. 1a), which together form a fine-scale redistribution of components often interpreted in the literature as an effective "diffusive" component of mixing. At the same time, in real multicomponent systems these mechanisms are accompanied by demixing processes (Fig. 1b), in particular segregation (III) and stratification (IV), which do not physically belong to mixing mechanisms but significantly affect the spatial organization and final structure of the mixture. Fundamental studies in granular mechanics have shown that the combination of convection, localized shear deformation zones, and segregation mechanisms forms complex spatial structures of component distribution that cannot be adequately characterized solely by integral statistical measures of mixture homogeneity [2, 17].

For feed materials with complex structural organization, this physical scheme is further supplemented by processes of structural rearrangement of the medium, which manifest differently depending on the material type.



a *b*

Fig. 1. Basic mechanisms of mixture structure formation in a multicomponent granular medium: a – combination of convective transport of material macro-volumes (I) and shear-induced microscopic particle displacements (II); b – manifestations of segregation (III) and stratification (IV) processes during mixing

For granular bulk components of feed mixtures, the dominant mechanisms are convective (kinematically driven) transport of material macro-volumes and shear-induced microscopic particle displacements within layers of localized flow, which in the literature are often interpreted as an effective "diffusive" component of mixing. At the same time, segregation mechanisms operate in such systems due to differences in particle size, density, or shape, manifesting in the formation of spatially stable zones dominated by individual components. Fundamental reviews in granular mixing theory emphasize that process efficiency in granular systems is determined primarily by the balance between macroscopic transport, localized shear, and segregation mechanisms, rather than solely by the intensity of circulation flows [2, 17].

In the presence of cohesive or cohesive–adhesive properties, the physical picture of the mixing process becomes significantly more complex. Interparticle adhesive forces promote the formation of agglomerates and clusters, which alter the scale and nature of microscopic particle displacements. In such systems, mechanisms of structural breakdown under shear stresses become decisive, and material deformation exhibits a pronounced localized character. Studies of cohesive granular flows show that particle cluster formation substantially affects the intensity of shear-induced mixing and the nature of velocity fluctuations within the flow [18]. For feed mixtures, this is important because fine fractions and moistened components may exhibit cohesive behavior and therefore require not only convective transport but also controlled agglomerate breakup within shear zones [18].

Fibrous materials occupy a special place among feed components, as the physical mechanisms of their mixing are governed by particle shape anisotropy, orientation within the flow, and a tendency toward mutual interlocking and entanglement, leading to the formation of spatial frameworks that restrict relative motion and suppress the "diffusive" component of mixing. DEM-based studies of elongated particles (spherocylinders) in drum systems show that particle shape significantly influences flow regimes, the degree of radial and axial migration, and the final mixture structure, thereby modifying the balance between convective transport and shear-induced microscopic displacements [19]. For fibrous feed components (straw, hay, stem fractions), this implies that the physical mechanism of "mixing" often involves not only transport but also reorientation of particles and the disruption or loosening of local entanglements within zones of intense shear [19].

For viscoplastic components exhibiting a yield stress, a fundamental factor is the division of the working volume into flowing and non-flowing (plug or unyielded) regions. In such media, mixing is limited to regions where the stress exceeds the yield stress; outside these regions the material may remain quasi-solid and become involved in the process only through gradual expansion of the flowing zone or changes in the excitation kinematics. Experimental studies of laminar mixing of model viscoplastic fluids in stirred vessels demonstrate that energy consumption and circulation times strongly depend on the degree of "viscoplasticity" (conditionally, the magnitude of the yield stress manifestation), which is directly related to the size of the region actively participating in mixing [20]. General flow patterns of viscoplastic media and the role of yield stress as a physical factor governing deformation localization are summarized in review studies on the experimental basis of yield-stress fluid flows [21]. In the context of feed mixtures, this provides a physically consistent framework for describing the mixing of components such as moist pulps, beet pulp, stillage, and similar materials, where the regime is determined not by the "type of mixer" but by the relationship between imposed stresses and the material yield stress [20, 21].

Generalization of the presented results indicates that mixing processes of feed materials are physically heterogeneous in nature and cannot be described by a single universal mechanism. For different material types, different combinations of macroscopic transport, localized deformation, structure formation, and demixing processes dominate, with their intensity and spatial distribution governed by the structural–mechanical behavior of the components (Fig. 2). At the same time, mixing efficiency is determined not so much by the kinematics of the apparatus itself as by the balance between zones of active material deformation and regions that remain weakly involved in the process. Such a physically oriented approach makes it possible to consider feed material mixing as a set of regimes determined by material properties and loading conditions, rather than solely by the design features of mixing equipment.

Fig. 2. Systematization of physical mixing mechanisms of feed materials with different structural–mechanical types

For a formalized analysis of feed material mixing processes, it is appropriate to separate the description of the physical mechanisms of the process from the generalized scientific language used to describe them. In this context, the mixing process is considered a multidimensional physicomechanical phenomenon whose behavior can be adequately represented in a coordinate space of physical and structural–topological descriptors (Table 1) that are invariant with respect to the specific apparatus design and the implemented operating regime. Within this framework, the coordinates of such a space should be understood as independent physicomechanical dimensions of process description, each reflecting a distinct aspect of the behavior of the material medium during mixing.

Table 1

Physical and structural–topological descriptors of the feed material mixing process

Code	Name	Physical meaning	Typical modes of realization
D1	Type of interparticle interactions	Nature of bonds between elements of the material medium that determines the microstructural basis of the process	– contact–frictional; – cohesive–adhesive; – geometrically oriented; – structurally bonded (with yield stress).
D2	Rheological response of the medium	Generalized form of material response to applied mechanical loading	– quasi-granular; – viscoplastic; – threshold; – combined.
D3	Character of deformation response	Spatial form of deformation realization within the material volume	– uniformly distributed; – localized; – intermittent; – quasi-rigid.
D4	Scale of active displacements	Level at which the dominant displacements of particles or their assemblies occur	– macroscopic transport of volumes; – mesoscopic rearrangement of layers and clusters; – microscopic relative displacements; – combined.
D5	Nature of energy dissipation	Spatial–temporal character of mechanical energy dissipation during mixing	– localized; – volume-distributed; – impulsive; – threshold-controlled.
D6	Flow structure	Geometry and organization of material motion within the working volume	– single- or multi-loop circulation; – presence of recirculation cores; – laminar-limited flow; – fragmented flow structure.
D7	Spatial organization of flow zones	Topology of the distribution of active and passive regions within the working volume	– continuous active zone; – local active regions; – combination of active zones with a passive volume; – dominance of passive zones.
D8	Degree of volume involvement	Fraction of material involved in deformation and motion	– full; – partial; – localized; – threshold involvement.
D9	Stability of spatial structure	Temporal stability or reconfiguration of flow patterns and flow zones	– stationary; – quasi-stationary; – periodically restructured; – unstable.

This approach is based on the assumption that, regardless of the type of feed material and the nature of process excitation, its evolution can be described by a limited yet sufficiently comprehensive set of generalized parameters that reflect the nature of interparticle interactions (D1), the rheological response of the medium (D2), the character of the deformation response (D3), the scale of active material displacements (D4), the nature of energy dissipation (D5), as well as the flow structure (D6), the spatial organization of flow zones (D7), the degree of volumetric involvement in deformation (D8), and the temporal stability of the formed spatial structure (D9).

A determining component of such a description is the nature of interparticle interactions (D1), which forms the microstructural basis of the material medium and defines the manner in which mechanical energy is transferred between its elements. It is precisely this microstructure that governs whether deformation is realized predominantly through contact–frictional interactions, cohesive–adhesive bonds, geometrically induced mechanical interlocking, or structural links associated with the presence of a yield stress. This microstructural basis is manifested in the rheological response of the medium (D2), which determines the general type of its behavior under external loading without specifying the particular flow mechanisms.

Another important coordinate of the description is the character of the deformation response (D3), which reflects the spatial form of deformation realization within the material volume. Deformation may be distributed, localized, continuous, or intermittent, which fundamentally affects the degree of material involvement in motion (D8). Closely related to this is the scale of active displacements (D4), which makes it possible to distinguish between processes dominated by macroscopic transport of volumes, mesoscopic rearrangement of layers and clusters, or microscopic relative displacements of individual particles.

A separate aspect of the description is the nature of energy dissipation (D5), which reflects the spatial–temporal distribution of mechanical energy dissipation within the material medium during mixing and represents a generalized characterization of internal losses without their quantitative evaluation. This descriptor complements the deformation–kinematic description of the process without introducing criteria of energy efficiency.

The next group consists of descriptors that reflect the spatial organization of motion, in particular the flow structure (D6) and the spatial organization of flow zones (D7). The flow structure may be represented by one or several circulation loops, recirculation cores, or fragmented flows, whereas the zonal organization is determined by the ratio of active and passive regions within the working volume. The combination of these characteristics forms the topological representation of the mixing process.

The final element of the description is the temporal stability of the formed spatial structure (D9), which characterizes the ability of the system to maintain or reorganize the configuration of flows and flow zones during operation and reflects the dynamic properties of the material medium.

Thus, the system of physical and structural–topological descriptors forms a universal coordinate space for describing feed material mixing processes without resorting to the analysis of specific mechanisms, operating regimes, or performance indicators. It is within this space that an ordered comparison of different process evolution scenarios and the development of integrated classification schemes become possible.

The presented descriptors and their typical modes of realization define the coordinate space for describing the mixing process and are not interpreted as indicators of quality or efficiency, which are considered at subsequent stages of the research.

In the mixing of multicomponent feed materials, different physical mechanisms of material transport and redistribution may manifest simultaneously, differing in the scale of displacements, the nature of deformation, and the spatial organization of flows. However, for specific properties of the material medium and conditions of its deformation, one of these mechanisms usually determines the overall kinematic and deformation pattern of the process. Within the scope of this study, such a mechanism is regarded as the dominant mixing regime (a generalized physical scenario) and is associated with characteristic values of key physical and structural–topological descriptors.

It should be emphasized that the identified mixing regimes do not represent equipment-related or hydrodynamic operating regimes (such as turbulent, fluidized, or vibratory), but rather fundamental physical scenarios of material transport and deformation that govern component redistribution independently of the structural type of the mixing apparatus and the method of process excitation [1, 2, 22].

Dominance of the convective regime corresponds to situations in which macroscopic transport of material volumes (D4), an ordered circulation flow structure (D6), and a high degree of material involvement in motion (D8) are decisive. Under this scenario, the deformation response is predominantly distributed (D3), and mixture composition equalization is achieved through repeated transfer of significant material masses between different zones of the working volume, which is consistent with classical concepts of convective mixing of dispersed media [1, 2, 23].

The shear regime is realized when localized shear deformations (D3) and a mesoscopic scale of active displacements (D4) dominate, such that component redistribution occurs mainly within shear layers or clusters. This regime is characterized by the concentration of mechanical energy in deformation zones (D5) and a limited role of macroscopic transport. Such correspondence between the regime and characteristic descriptors is well aligned with the physics of granular and viscoplastic media [23, 24, 26].

Within the present analysis, the diffusive regime is considered conditional and corresponds to processes in which microscopic relative particle displacements (D4) dominate under a uniformly fine-scale deformation response (D3) and a significant degree of material involvement in motion (D8). In this case, a pronounced circulation flow structure is absent (D6), and mixture composition equalization occurs without substantial macroscopic transport, which corresponds to the classical interpretation of the diffusive component of mixing [1, 22].

Dominance of the segregation regime is associated with the realization of demixing processes, which are characterized by a fragmented flow structure (D6), a combination of active and passive zones within the working volume (D7), and selective involvement of material in deformation (D8). Under such conditions, differences in the physical properties of components determine their spatial self-organization, while stratification is regarded as a specific manifestation of this regime [2, 17, 24, 25].

The localized flow regime corresponds to scenarios in which deformation and material motion are concentrated within limited zones (D3), whereas the main part of the volume behaves as a quasi-solid mass. Such behavior is associated with the threshold nature of the rheological response of the medium (D2), localized mechanical energy dissipation (D5), and threshold or partial involvement of material in motion (D8), which is typical of structurally bonded and viscoplastic materials [24, 26].

Thus, the dominant mixing regimes–convective, shear, diffusive (conditional), segregation-dominated, and localized flow–exhibit a clear correspondence with the system of physical and structural–topological descriptors presented in the table and reflect fundamental physical scenarios governing the mixing of feed materials [1, 2, 17, 22–26].

Within the framework of this study, the integrated classification of feed material mixing processes is interpreted as a procedure for assigning a specific process to a class based on a set of physically significant attributes that reflect the structural–mechanical nature of the material medium, the dominant transport and deformation scenario (dominant process regime), and demixing pressure as a factor opposing homogenization. The process class is introduced in the form of a compact engineering code:

$$K = \langle M - R - \Sigma \rangle, \tag{1}$$

where $M \in \{G, C, F, Y\}$ denotes the type of material medium (G – granular, C – cohesive, F – fibrous, Y – yield-stress viscoplastic); $R \in \{CV, SH, DF, SG, LT\}$ denotes the dominant process regime as a generalized physical scenario (CV – convective, SH – shear, DF – diffusive, SG – segregation-dominated, LT – localized flow); $\Sigma \in \{S0, S1, S2\}$denotes the demixing pressure index (S0 – low, S1 – moderate, S2 – high).

Such a notation captures the physical meaning of the process independently of the structural type of the apparatus, as it is based on transport and deformation scenarios rather than on equipment-related or hydrodynamic operating regimes.

The selection of the dominant regime $R$is formalized as a problem of maximizing a scenario dominance index. Let $D = \{D_1, \dots, D_9\}$denote the set of introduced physical and structural–topological descriptors of the process. Then, the dominant regime is determined according to the rule:

$$R \quad = \arg\max_{r \in \mathcal{R}} \quad I_r(\mathrm{D}), \mathcal{R} = \{\mathrm{CV}, \mathrm{SH}, \mathrm{DF}, \mathrm{SG}, \mathrm{LT}\}, \tag{2}$$

where $I_r(D)$is a generalized index of *consistency* between the observed process pattern and scenario r.

To ensure an unambiguous comparison of scenarios, it is advisable to define this index in a normalized form (in order to eliminate dependence on the number of involved attributes):

$$I_r(\mathrm{D}) = \frac{\sum_{j \in \mathcal{J}_r} w_{rj}\, \varphi_{rj}(D_j)}{\sum_{j \in \mathcal{J}_r} w_{rj}}, 0 \le I_r \le 1, w_{rj} > 0, \tag{3}$$

where J_r is the subset of descriptors relevant to scenario r; $\varphi_{rj}(D_j) \in [0,1]$ is a membership (compatibility) function that characterizes the correspondence between the actual manifestation of descriptor $D_j$and the typical form of scenario r; w_{rj} are weighting coefficients that reflect the priority of individual descriptors for a given scenario (for example, for the LT scenario the determining descriptors are D_2, D_3, D_7, D_8, whereas for the CV scenario they are D_4, D_6, D_8).

For cases in which several scenarios are comparable in terms of their degree of manifestation, a normalized dominance vector is introduced:

$$p_r = \frac{\exp(\beta I_r)}{\sum_{q \in \mathcal{R}} \exp(\beta I_q)}, \sum_{r \in \mathcal{R}} p_r = 1, \tag{4}$$

where p_r is the fraction (probability) of realization of scenario $r$in the overall process structure; q is the scenario index that runs over all possible regimes from the set R; I_q is the index of consistency between the process evolution and scenario q, used to normalize the dominance vector; $\beta > 0$ is a sensitivity parameter controlling scenario separation: as $\beta \to \infty$, a hard assignment of the dominant regime is obtained, whereas for finite values of β a multi-scenario description is allowed.

The demixing pressure Σ is introduced as a class attribute that reflects the system's ability to form stable spatial heterogeneity as a result of segregation–stratification phenomena. Within a qualitative classification framework, Σ is appropriately defined through a demixing risk index:

$$\Pi = \sum_{k=1}^{m} a_k \ \psi_k, \tag{5}$$

where ψ_k are binary or graded indicators of the presence of «drivers» of demixing (for example, differences between components in particle size distribution, density, or shape; the formation of fragmented flows and passive zones; the presence of stable stratification), and a_k are weighting coefficients.

Further discretization of the index Πmakes it possible to assign the process to one of the levels $\Sigma = S_0, S_1, S_2$. Within this approach, segregation is treated as a dominant process regime of a demixing nature, which may either accompany homogenizing transport and deformation scenarios or become determining in cases where the index $I_{SG}$is comparable to or exceeds the indices of homogenizing regimes.

In real multicomponent feed mixtures, spatial–zonal heterogeneity of scenarios is admissible (for example, the simultaneous existence of regions of convective circulation and zones of localized flow). In such cases, the process may be described by a composition of classes:

$$K_{\text{mix}} = \sum_{i=1}^{n} \alpha_i \ K_i, \alpha_i \geq 0, \sum_{i=1}^{n} \alpha_i = 1, \tag{6}$$

where α_i represents the fraction of the volume or the fraction of time during which class K_i is realized. This formulation makes it possible to interpret mixing as a set of local physical scenarios without reducing the process to a single averaged regime.

Figure 3 presents a physically substantiated operational scheme for assigning a mixing process class, which reflects the sequence of physical constraints and admissible scenarios of material transport and deformation.

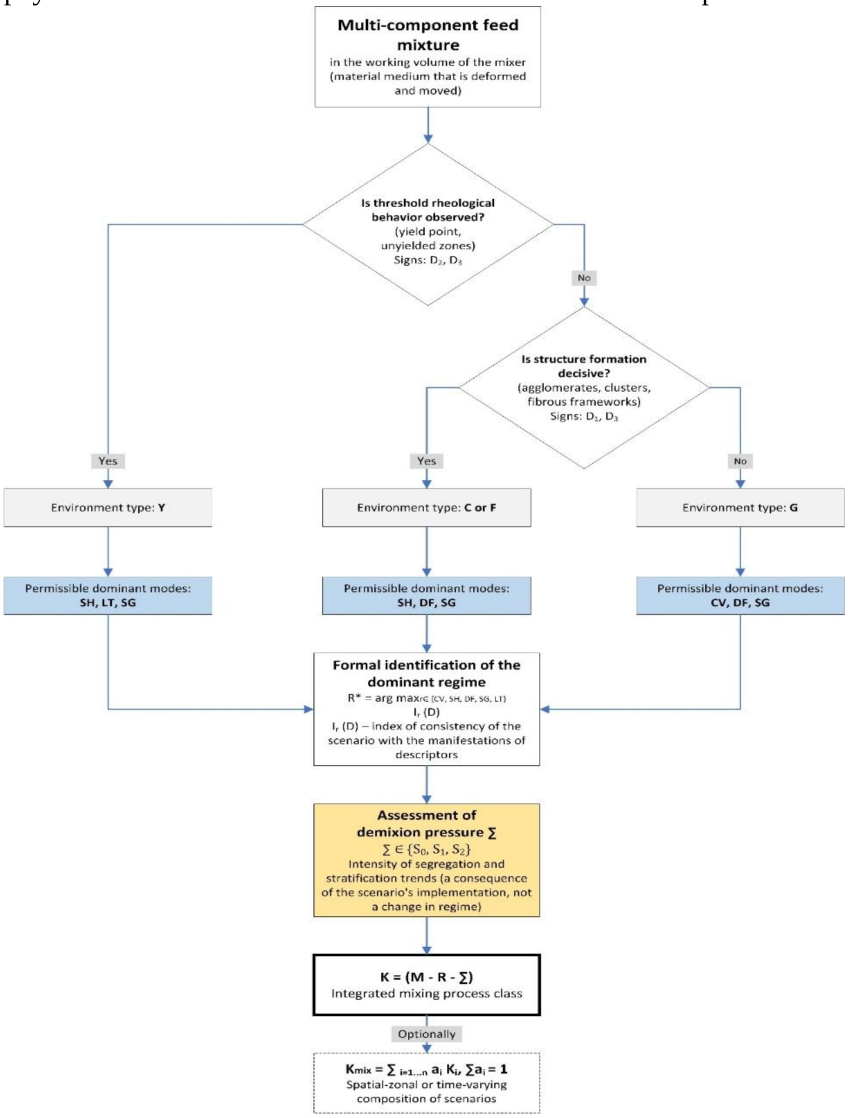


Fig. 3. Operational scheme (decision tree) for assigning a mixing process class based on material behavior characteristics and manifestations of transport/deformation scenarios.

The scheme does not determine the dominant regime directly; instead, it delineates the domain of admissible scenarios for different types of material media, within which the formal framework based on the consistency indices $I_r(D)$ identifies the dominant regime and subsequently forms the integrated process class $K = \langle M - R - \Sigma \rangle$. Such an approach ensures invariance of the classification with respect to the structural type of the mixing apparatus and enables a correct consideration of both homogenizing and demixing process scenarios.

The generalization of the results of the classification procedure is presented in the form of a class matrix (Table 2), which systematizes the admissible combinations of the material medium type M, the dominant regime R, and the demixing pressure index Σ, and represents their characteristic physical manifestations through the corresponding process descriptors.

Table 2

Integrated classification of feed material mixing processes

M	**R**	**Σ**	**Physical meaning of the class**	**Typical descriptor manifestations**	**Engineering interpretation**
G	CV	S0–S1	Convective homogenization with volumetric transport	D4 – macroscopic transport; D6 – circulation flows; D8 – high degree of involvement	Efficient mixing of granular components
G	DF	S0	Fine-scale homogenization without pronounced circulation	D4 – microscopic displacements; D3 – uniformly distributed response	Slow but stable homogenization
G	SG	S1–S2	Dominance of demixing over homogenization	D6 – fragmented flows; D7 – passive zones	Segregation and stratification of the mixture
C	SH	S0–S1	Shear mixing with agglomerate breakup	D1 – cohesive bonds; D3 – localized shear	Requirement for intensive deformation
C	DF	S0	Limited fine-scale homogenization	D4 – microscopic displacements; D5 – localized dissipation	Secondary mixing regime
C	SG	S1–S2	Clustering and demixing	D7 – zonal organization	Inefficient mixing
F	SH	S0–S1	Shear with reorientation of fibers	D1 – geometrical interactions; D3 – intermittent deformation	Loosening of fiber entanglements
F	SG	S1–S2	Spatial stratification of fiber	D6 – fragmented flows	Deterioration of homogeneity
Y	LT	S0–S1	Localized flow above the yield stress	D2 – threshold response; D3 – deformation localization	Mixing limited to active zones
Y	SG	S1–S2	Demixing in a threshold medium	D7 – passive regions	Homogenization is practically unattainable

The classification presented in the table does not represent an exhaustive list of all formally possible classes of mixing processes. It reflects the physically realizable and engineering-relevant core of classes characteristic of feed materials and TMR technologies. Other combinations of the parameters M, R, and Σmay correspond to transitional, local, or unstable process scenarios and therefore are not considered as independent classes within the scope of this study.

5. Conclusion

Based on the results of the conducted study, it has been established that the mixing processes of multicomponent feed materials have a complex physical nature and are governed by the interaction of several heterogeneous mechanisms of transport, deformation, and structural reorganization of the material medium. It is shown that the efficiency of forming a homogeneous mixture cannot be explained solely by the kinematics of the mixing apparatus or by the intensity of circulation flows; rather, it is determined by the balance between zones of active material deformation and regions that remain weakly involved in the process.

The analysis demonstrates that homogenization of feed mixtures is achieved mainly through a combination of convective transport of material macro-volumes, shear-induced displacements, and fine-scale restructuring of the medium, whereas segregation and stratification act as accompanying demixing phenomena that can significantly limit the attainment of spatial uniformity. The intensity and manifestation of these processes depend strongly on the structural–mechanical nature of the feed components, particularly their frictional, cohesive, fibrous, or viscoplastic properties.

The approach proposed in this work for describing the mixing process is based on a system of physical and structural–topological descriptors, which enables a generalized characterization of material behavior without reference to the structural type of equipment. Such a description allows the physical essence of the process to be separated from its apparatus implementation and ensures invariance of the analysis with respect to specific mixer designs and operating regimes. By correlating the characteristic manifestations of the introduced descriptors, dominant physical scenarios governing the mixing process have been identified, reflecting different modes of material transport and deformation within the working volume. It is shown that, for given material properties, one of these scenarios determines the overall kinematic and deformation pattern of the process, while the others play auxiliary or competing roles.

The generalization of these findings results in the formulation of an integrated, physically oriented classification of feed material mixing processes, in which the process type is defined by the combination of the structural–mechanical nature of the medium and the dominant scenario of deformation and transport, taking into account demixing effects. The proposed classification enables a clear distinction between homogenizing and demixing regimes without recourse to apparatus-related or hydrodynamic criteria.

Formalization of the classification in the form of a compact engineering notation and an operational procedure for process class identification creates the prerequisites for its practical application in the analysis and design of mixing technologies. The obtained results can serve as a theoretical basis for further quantitative analysis of mixing processes, optimization of feed mixer operating regimes, and the justified selection of their structural and technological parameters.

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ФІЗИЧНІ ПРИНЦИПИ ТА КЛАСИФІКАЦІЯ ПРОЦЕСІВ ЗМІШУВАННЯ КОРМОВИХ МАТЕРІАЛІВ

Процеси змішування багатокомпонентних кормових матеріалів характеризуються складною фізичною природою, зумовленою поєднанням різних механізмів перенесення, деформації та структурної перебудови матеріального середовища. У реальних технологіях приготування кормових сумішей одночасно взаємодіють сипкі, когезивні, волокнисті та в'язкопластичні компоненти, що призводить до формування різних режимів руху матеріалу та ускладнює досягнення стабільної просторової однорідності. Наявні класифікації процесів змішування переважно орієнтовані на конструктивні особливості обладнання або окремі групи матеріалів і не забезпечують узагальненого фізично обґрунтованого опису процесу.

Метою роботи є формування інтегрованої, фізично орієнтованої класифікації процесів змішування кормових матеріалів, інваріантної до конструктивного типу змішувального апарата. Методологічною основою дослідження є системний аналіз сучасних теоретичних і *експериментальних робіт з фізики змішування, механіки гранулярних і когезивних середовищ та реології в'язкопластичних матеріалів.*

У роботі систематизовано базові фізичні механізми змішування та введено систему фізичних і структурно-топологічних дескрипторів, що дозволяють узагальнено описувати перебіг процесу незалежно від апаратної реалізації. На основі аналізу проявів цих дескрипторів ідентифіковано домінуючі режими перебігу процесу як узагальнені фізичні сценарії перенесення та деформації матеріального середовища. Запропоновано інтегровану класифікацію процесів змішування кормових матеріалів, у якій клас процесу визначається поєднанням структурно-механічної природи середовища та домінуючого режиму з урахуванням деміксійних проявів.

Отримані результати створюють теоретичну основу для подальшого кількісного аналізу процесів змішування, оптимізації режимів роботи кормозмішувачів та обґрунтованого вибору їх конструктивних і технологічних параметрів.

Ключові слова: *багатокомпонентні суміші, фізична взаємодія, механізми перенесення, домінуючі режими, структурна організація, деміксія, сегрегація, інженерна типологія, змішувальні апарати.*

Ф. 6. Рис. 3. Табл. 2. Літ. 26.

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