№ 3 (130) / 2025
Vol. 130, № 3 / 2025
Техніка, енергетика, транспорт АПК
UDC 636.2.084:631.3:519.876.5
DOI: 10.37128/2520-6168-2025-3-3

SYSTEM MODEL OF THE MIXING PROCESS IN THE FEED PREPARATION TECHNOLOGICAL CHAIN

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The article examines the role of the feed-mixing process within the technological chain of feed preparation and its significance in ensuring the stable quality of feed mixtures and improving the energy efficiency of agricultural machinery. The purpose of the study is to provide a systematic generalization of the factors, methods, and criteria for evaluating the efficiency of the mixing process and to identify scientific and methodological gaps that limit further development of mixer designs and operating regimes. The research methodology combines system analysis, mechano-technological modeling, and a comparative-analytical approach to process evaluation. A comprehensive review of scientific and patent-technical sources was conducted, and current solutions in vertical mixer design and efficiency assessment methods were analyzed. A structural-logical model of the mixing process was developed, comprising three interrelated subsystems: material, energy, and informational. Within this model, three interaction levels were distinguished: input parameters (material properties), control influences (machine design and operating parameters), and process outcomes (quality and energy indicators). A classification of factors determining mixing efficiency was generalized into three groups – material, technological, and constructive – with indication of key parameters and influence criteria.

Methods for assessing mixing efficiency were analyzed, including physico-chemical, physico-mechanical, energetic, and digital (intelligent-modeling) approaches. Generalized quality and energy efficiency criteria were proposed. It was established that existing methods remain fragmented and fail to comprehensively account for the interaction within the "machine–material–process" system. The need for the development of mechano-technological models of mixing that consider the rheological properties of feed materials, parameters of working elements, and operational modes was substantiated. The potential of CFD and DEM numerical modeling, combined with Smart Feeding sensor systems, was emphasized as a tool for adaptive real-time process control.

The obtained results form the theoretical and methodological basis for further research aimed at optimizing mixer designs, reducing specific energy consumption, and improving the stability of feed mixture quality under industrial conditions.

Key words*: feed mixer; feed mixing; quality and energy indicators; influencing factors; mechano-technological system; structural-logical model; system model; process evaluation criteria.*

Eq. 2. Fig. 2. Table 4. Ref. 20.

1. Problem formulation

Rational feeding of farm animals is a key factor in the efficiency of livestock production, as it directly determines the level of nutrient utilization, productivity, and overall economic performance of the industry [1].

In the context of industrialization and automation of livestock enterprises, the formation of total mixed rations (TMR) acquires system-forming importance, ensuring the stability of feed composition and the balanced supply of nutrients. This, in turn, increases the efficiency of nutrient conversion into livestock products and reduces the risk of differential consumption of feed components [2].

In modern technological feed preparation lines, the mixing process is a key operation that implements these requirements at the technological level – it ensures the homogenization of components with different physico-mechanical properties (roughage, succulent, concentrated, and liquid feeds) and determines the final quality parameters of the feed mixture.

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

Despite the high level of mechanization of feed preparation processes, further improvement of mixer designs and operating modes remains an urgent task, since the heterogeneity of the physico-mechanical properties of feed materials significantly affects the mixing quality and energy efficiency of the process.

2. Analysis of recent research and publications

Studies show that reducing the batch volume in the same mixer from 100% (10 t) to 50% (5 t) of loading decreases the coefficient of variation (CV) from 34.6% to 2.6%, while optimizing the kinematic parameters of the mixing tool at a medium loading level (≈ 75%) further reduces it from 12.0% to 4.6% [3]. Results of other experimental studies indicate that feed mixtures with increased bulk density reach a coefficient of variation (CV) below 10% after only 60 s of mixing [4]. This demonstrates that the physico-mechanical properties of feed materials significantly influence the kinetics of the mixing process: materials with higher bulk density achieve a technologically acceptable degree of homogeneity more quickly, creating prerequisites for reducing time and energy consumption and for implementing adaptive control of mixing modes. In industrial practice, a CV level below 10% is considered excellent, while values within 10–15% are regarded as a satisfactory indicator of mixture uniformity [5]. An insufficient degree of mixing leads to higher composition variability between individual portions, indicating decreased stability and reproducibility of the technological process [6].

The technological role of the mixing process lies not only in achieving homogeneity but also in ensuring coordination between the preceding stages (grinding, dosing) and the subsequent ones (transporting, distribution), since the efficiency of the entire feed-preparation system depends on this integrative link of the production cycle. Therefore, the main process parameters (duration, intensity, kinematic regimes of the working tools, hopper filling degree, etc.) must be optimized considering the physico-mechanical properties of feed materials (bulk density, moisture, angle of repose, viscosity, etc.).

Despite the considerable number of studies aimed at improving the design elements of mixers (in particular augers, blades, and mixing chambers), a systemic investigation of the mixing process as a technological phenomenon remains insufficiently developed. There is a particular lack of generalized models describing the relationship between geometric and kinematic parameters, mixing quality, and energy efficiency. Under current trends toward intelligent management of production processes, there is an increasing need to reinterpret mixing within the «Smart Feeding» concept – using sensors, optimization algorithms, and adaptive real-time parameter control [7].

Given the above, further scientific research on the mixing of feed materials should be directed toward forming a holistic understanding of this process as a key technological link in the livestock feeding system. Considering the multifactorial nature of the phenomenon and its impact on the efficiency of feed-preparation lines, it is necessary to generalize existing theoretical and applied approaches, refine the underlying regularities, and determine the directions for further process optimization.

3. The purpose of the article

The aim of the study is to generalize the scientific and technological foundations of the feed mixing process within the livestock feeding system, with an emphasis on its role in ensuring the efficiency, energy saving, and technological reliability of modern feed-preparation systems.

To achieve this goal, the following tasks must be addressed:

- to identify and analyze the main scientific and technical directions in the study of feed material mixing processes within livestock feed-preparation systems, in particular to determine key approaches to evaluating mixing efficiency;
- to develop a structural and logical scheme of the mixing process in the feed-preparation system that reflects its interconnections with preceding and subsequent technological operations;
- to design a conceptual system model of the feed mixing process within the technological chain of feed preparation, which reflects the main interrelations between system elements and can be used for further formalized description of mechanico-technological regularities;
- to summarize the factors determining the quality of the mixing process and to classify them according to their nature of influence (material properties, technological parameters, design features of the machines);
- to analyze the methods and criteria for evaluating the efficiency of the mixing process, determining their informativeness and applicability under production conditions;
- to identify scientific and methodological gaps in the study of feed material mixing processes that require further elaboration in the context of analyzing the design and operating modes of feed mixers.

4. Results and discussion

The methodological basis of the study is founded on systemic and structural-functional approaches, which imply the consideration of the mixing process as an integrated element of the technological system for feed preparation and distribution in livestock production. This approach makes it possible to study the process not in isolation, but in connection with the preceding and subsequent operations of the feed-preparation cycle, thereby providing a comprehensive understanding of its influence on the overall efficiency of the feeding system. Within this framework, the mixing process was regarded as a multifactorial phenomenon simultaneously influenced by the physico-mechanical properties of materials, the design parameters of machines, and their operating modes.

The study has an analytical and review character and is based on the generalization of scientific, technical, and regulatory sources. The information base consisted of publications in international and domestic journals, current international and national standards, analytical reports, as well as materials from patent databases (EPO, USPTO, CNIPA, and Ukrpatent). Source selection was carried out according to criteria of scientific significance, novelty (mainly publications from the last 10-15 years), thematic relevance (feed mixing, TMR technologies, process parameters), and the presence of quantitative characteristics or model descriptions.

To achieve the research goal, a set of analytical and comparative methods was applied, ensuring a comprehensive study of the problem. The analytical method was used to systematize and generalize literature and patent sources; the comparative-analytical method – to compare approaches of different scientific schools and technological systems; the classification method – to group the factors affecting mixing quality; and the graph-analytical method – to construct generalized schemes and structural-logical diagrams of the process.

The research logic was based on a step-by-step systemic analysis of the feed material mixing process within the technological chain of feed preparation. At the first stage, a review of scientific, technical, and patent sources was conducted, which made it possible to determine modern trends in mixer design development and to identify the main factors affecting process efficiency. At the second stage, these factors were systematized according to the nature of their influence (material, technological, and structural), and a structural-logical model of the process was developed, reflecting the interrelations between the material, energy, and information subsystems. The third stage involved the analysis of existing methods and criteria for assessing mixing quality and energy efficiency, including the coefficient of variation, standard deviation of concentration, and specific energy consumption, with an assessment of their informativeness and applicability under production conditions. At the final stage, scientific and methodological gaps in the study of the mixing process were identified, and the need for further research was substantiated – particularly in analyzing mixer designs, operating modes, and the development of mechanico-technological models of the process.

The research methodology has a theoretical and analytical orientation and does not involve experimental measurements. Its outcome is the formation of a generalized scientific and technological model of the feed material mixing process, which reflects the relationships between component properties, machine parameters, and mixture quality indicators. The obtained generalizations form a foundation for future applied studies aimed at improving mixer designs, determining optimal operating modes, and developing adaptive real-time control systems for the mixing process.

The process of mixing feed materials in modern livestock production is a complex multifactorial phenomenon that combines mechanical, technological, and rheological aspects of interaction among components of different nature. The study of the regularities of this process has evolved along several scientific and technical directions, which have formed the theoretical and methodological basis for developing highly efficient mixing machines and technological feed-preparation systems.

The most common direction is the mechanical-technological approach, which is based on analyzing the geometry of mixer working tools, kinematic regimes, and the influence of design parameters on mixture quality. Its core assumption is that the degree of homogenization of the material depends on the intensity of particle movement within the working volume and on the amount of energy transferred from the working tool to the feed mass. The development of this approach is associated with the works [3] and [6], which investigated the influence of hopper filling level, auger shape, blade inclination angle, and rotational speed on the coefficient of variation (CV) of the mixture. Experimental studies have established that maintaining an optimal ratio of loading height to auger diameter ($h/D \approx 1.0$–1.2) ensures intensive circulation of the feed mass and reduces the coefficient of variation nearly twofold compared to non-optimal filling regimes, while the specific energy consumption for mixing decreases on average by 15–20%.

Researchers have also paid particular attention to vertical auger mixers, which provide intensive material circulation along the height of the hopper. Their performance efficiency depends on the configuration of auger flights, the inclination angle of knives, and the geometry of the hopper bottom. Several studies [4, 5] have demonstrated that intensifying the vertical flow while limiting radial displacement helps reduce stagnant zones and ensures stable mixture quality regardless of feed type.

The application of energy analysis within the mechanical-technological approach has made it possible to quantitatively assess the specific energy consumption per unit mass of the feed mixture and to identify the patterns of its variation depending on the filling level and kinematic parameters of the mixer. The obtained results formed the basis for establishing energy-saving operating regimes for the machines [6]. Thus, the mechanical-technological research direction is primarily focused on improving equipment design and optimizing its functional parameters.

The stochastic approach considers mixing as a random process of particle movement in space that follows the laws of statistical equilibrium. This approach is mainly applied in food and powder engineering but is increasingly used in feed-preparation systems as well. Classical mixing models – the diffusion, kinetic, and discrete element (DEM) models – describe the dynamics of the process through changes in the coefficient of variation over time [8, 9]. According to the model proposed by D. Muzzio [10], the mixing process in screw-type devices follows an exponential law of decreasing non-uniformity:

$$CV_t = CV_0\, e^{-kt}, \tag{1}$$

where k is the kinetic mixing coefficient that characterizes the rate of homogeneity attainment and depends on the geometry of the working chamber, the shear rate, and the design of the mixing elements. For feed mixtures, experimental studies have shown that the k parameter ranges between 0.03–0.12 s^{-1}, which allows determining the mixing duration required to reach a technological level of CV ≤ 10 % [6, 9].

Stochastic models of the mixing process make it possible to predict the degree of homogenization under varying physico-mechanical properties of the material (bulk density, moisture content, etc.), providing the basis for implementing adaptive algorithms to control process duration in Smart Feeding intelligent systems.

For the mixing of materials with increased moisture content (silage, beet pulp) and semi-liquid or liquid components (distiller's grains, molasses, syrup, water, liquid additives), the rheological approach becomes relevant, as it accounts for the viscous properties of the mass and the hydrodynamics of internal flows. In the studies by Zhang et al. [11] and Wang et al. [12], it was established that high-moisture feed materials exhibit Bingham or pseudoplastic rheological behavior: below a certain yield stress threshold, the material behaves as an elastic-plastic medium, and once this threshold is exceeded, its viscosity decreases with increasing shear rate. This necessitates consideration of rheological parameters when designing mixing tools, especially in combined screw-blade mixers.

The use of Computational Fluid Dynamics (CFD) modeling has enabled researchers to determine velocity distribution and turbulence zones in mixers of different geometries, significantly deepening the understanding of the process. In particular, Li et al. [13] demonstrated that optimizing the blade inclination angle by 15–20° improves mixture homogeneity by 12–18 % while simultaneously reducing specific energy consumption. Thus, the rheological approach is both promising and justified, as it integrates classical continuum mechanics with applied objectives of energy saving and digital flow modeling.

A modern integrated approach within the Smart Feeding concept combines sensor systems, digital models, and optimal control algorithms. According to this approach, the main process parameters (moisture, temperature, load, duration, coefficient of variation) are monitored in real time using Internet-of-Things (IoT) platforms. The obtained data are analyzed through digital models and machine learning algorithms, enabling system-state prediction and adaptive control of mixing regimes [7, 14]. Studies by Bach et al. [7] showed that using sensor-based control of mass and moisture during feed dosing and mixing increases mixture uniformity by 8–12 % and reduces energy consumption by 10–15 %. In industrial TMR systems of leading manufacturers such as Trioliet and Jay-Lor [15, 16], similar principles have already been implemented, confirming the practical effectiveness and technological maturity of the Smart Feeding concept, which should be regarded as a modern paradigm of mixing process management—integrating mechanical-technological and informational approaches to achieve maximum productivity and process stability.

Thus, the evolution of scientific and technical approaches to the study of feed mixing processes has progressed from empirical and mechanical models to stochastic, CFD, and digital control systems. Today, the most effective are combined approaches that integrate mechanical, energetic, and informational aspects of the process. Their implementation forms the foundation for developing adaptive real-time mixing control systems that meet the current requirements of energy-efficient and intelligent livestock production.

A synthesis of scientific and technical approaches to the study of feed preparation and mixing processes indicates that further development of feed-preparation technologies requires a systemic representation of the technological chain as a single controllable system (Fig. 1), in which each operation simultaneously completes the previous one and initiates the next. Each technological stage generates a set of output parameters (physico-mechanical, structural-mechanical, energetic, qualitative, etc.) that serve as input conditions for the subsequent operation and directly determine its efficiency, energy consumption, and process stability.

For instance, preparatory operations and mechanical processing form the basic material properties (ρ, W, φ, d, etc.) that influence dosing accuracy; in turn, dosing establishes mass and volumetric ratios (m_i, V_i, C_i, etc.) that determine the initial homogeneity of mixing. The mixing operation forms a set of qualitative and structural indicators (CV, S_{st}, H), determining mixture stability during transport and storage, which, in turn, defines the consistency of the final mixture structure and sets the delivery parameters (E_{sp}, S_r, Q_r) that affect the uniformity and efficiency of the final feed distribution process (CV_{feed}, L_r).

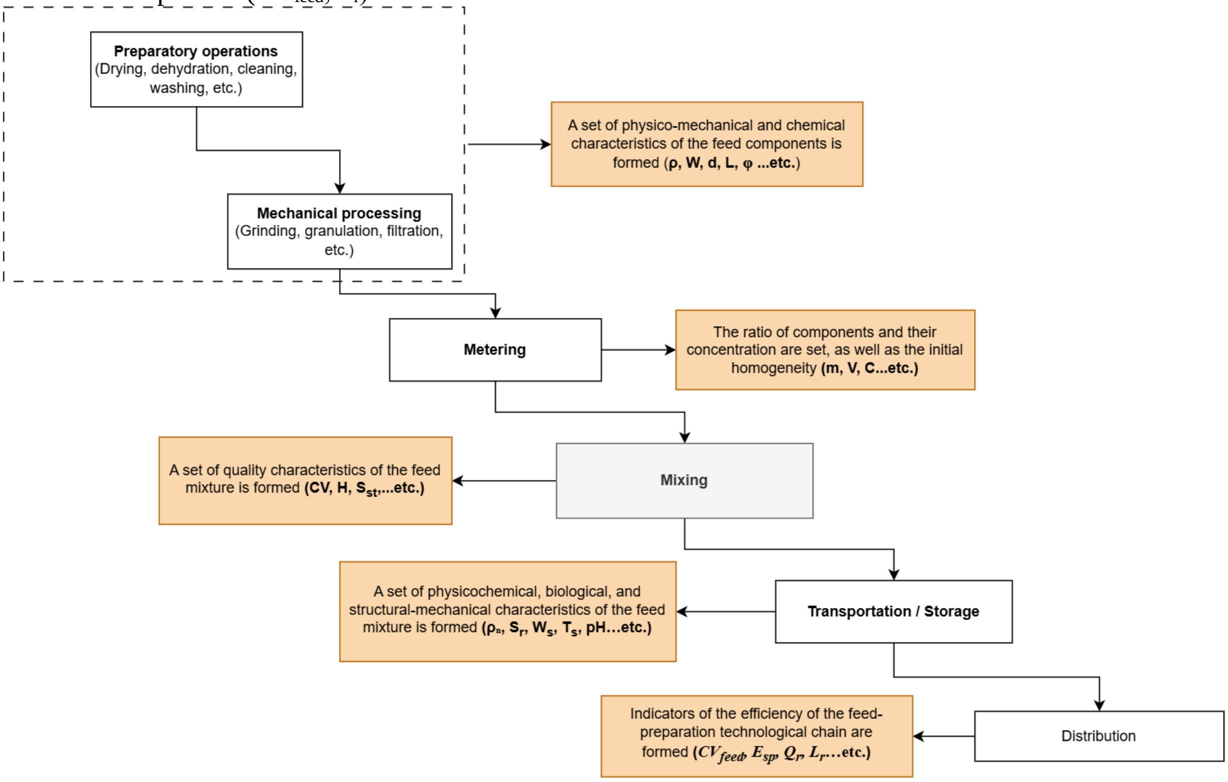

Fig. 1. Structural and logical model of parameter formation and transmission in the technological chain of feed mixture preparation and distribution

Thus, the structural-logical scheme of the processes of feed preparation, mixing, and distribution reflects the sequential formation and transfer of parameter complexes between technological operations, which are interconnected by cause-and-effect relationships. These interconnections determine the mixture quality, energy efficiency, and operational reliability of the entire feed-preparation system. Among these operations, the mixing process plays a key role – it defines the uniform distribution of nutrients and the stability of the physico-mechanical characteristics of the feed mass. Therefore, the mixing process should be considered from a systemic perspective (Fig. 2), which involves analyzing the interaction among the material, energy, and information subsystems [3, 5, 6].

From a structural and logical standpoint, the mixing process should be considered as an integrated system composed of three interacting subsystems – material, energy, and information. Their coordinated operation determines the trajectory of matter and energy flows, as well as real-time control of operating modes [7, 14-16, 17-20].

The material subsystem describes the spatio-temporal dynamics of particle movement and interaction within the working volume. Its state is determined not only by the physical-mechanical and rheological properties of the components (ρ, W, d, φ, etc.), but also by control inputs associated with the design parameters of the working elements (auger geometry, pitch of the spiral, configuration of knife elements) and the technological operating modes of the machine (ω, t, V_x, etc.). Due to the presence of feedback loops, the material subsystem represents an open system in which variations in energy load or control signals from the information subsystem directly transform velocity fields, shear deformation intensity, and the rate of mixture homogenization [11, 12].

The energy subsystem reflects the process of transmission and conversion of drive energy into mechanical work of shear and transportation of feed particles within the mixer's working volume. Its primary function is to ensure the required energy potential for the realization of the motion patterns of the material subsystem and stabilization of the technological mixing regime. The main parameters of the energy subsystem that determine the energy balance of the system and the limits of energy efficiency are drive power (N), kinematic mode of the working element (ω or n), torque (T), and integral energy indicators of the process (Esp, ηE, Ncp, $P_{Вт}$, etc.). The configuration of the working elements (type and geometry of the auger, blade inclination angle, shape of the bunker bottom, etc.) and the loading mode determine the nature of energy distribution in the material medium – that is, the intensity of shear stresses, turbulence, and uniformity of velocity fields. Accordingly, variations in energy parameters directly affect the rate of homogenization, flow stability, and mixture structure [3, 6].

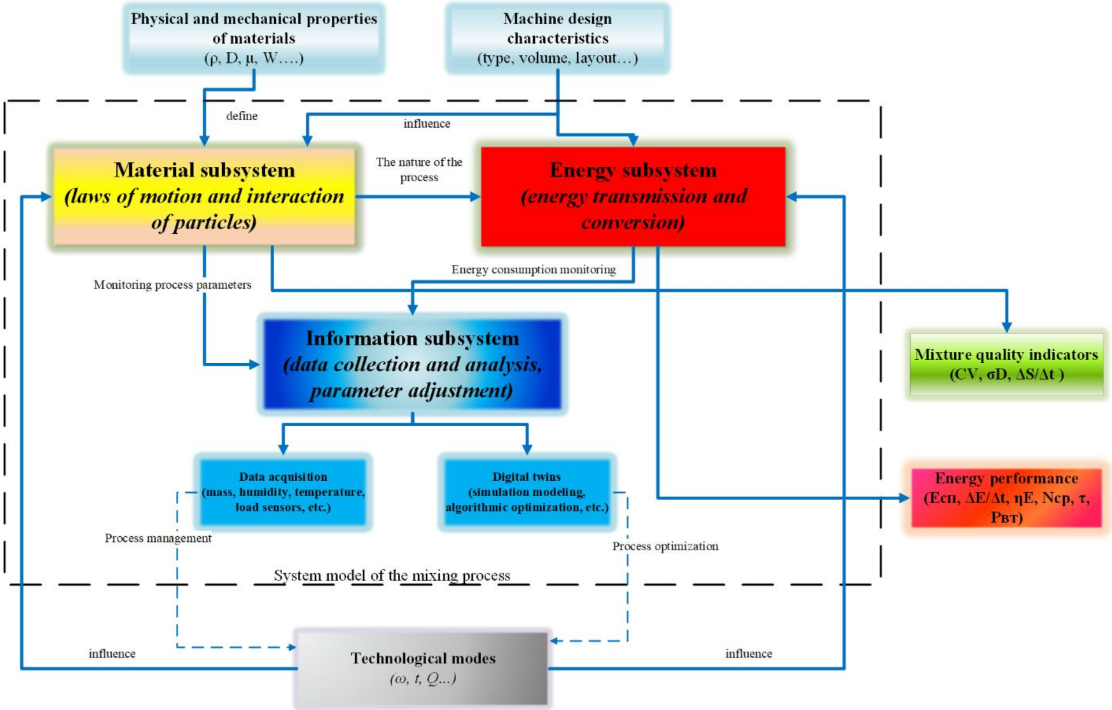

Fig. 2. System model of the feed material mixing process within the feed preparation technological chain

In the system interaction, the energy subsystem receives control signals from the information subsystem, which are implemented through automatic regulation of power parameters (N), angular velocity (ω), and torque (T) depending on the load, mixture homogeneity level (CV), or other monitored indicators. In the reverse direction, it transmits data on current energy consumption, energy efficiency, and mechanical overloads to the information subsystem, providing feedback on the basis of which digital monitoring and adaptive real-time control of the process are implemented.

Within system analysis, the interaction of the material, energy, and information subsystems is considered through the prism of three hierarchical levels of organization of the mixing process, which reflect the sequence of converting input influences into the resulting system characteristics.

The first level (input data) is determined by the physical-mechanical, structural-rheological, and chemical-technological properties of feed materials (density (ρ), moisture (W), particle size distribution (d), angle of repose (φ), friction coefficient (μ), viscosity (η), yield stress (τ_0), etc.), which form the initial conditions of particle interaction within the working volume, determine the flow behavior of the mixture (pseudoplastic, dilatant, Bingham-type, etc.) [11, 12], influence the structure of the material subsystem, and define the parameters of the energy interaction between the working elements and the medium.

The second level (control influences) includes technological modes (angular velocity (ω), mixing duration (t), degree of fill (ψ), etc.) and design parameters of the machines (type, diameter, pitch and profile of the auger, knife arrangement, body shape, blade geometry, etc.). At this level, the influence of the energy and information subsystems is implemented, ensuring the transmission of drive energy to the working elements, load monitoring, and automated real-time adjustment of operating modes [15-17]. Optimization of control parameters is performed with consideration of mixture properties, ensuring the required intensity of circulation flows, minimization of dead zones, and reduction of specific energy consumption [6, 17].

The third level (process results) reflects the output characteristics of the mixing system, which are divided into qualitative indicators (coefficient of variation (CV), component distribution dispersion (σD), structural stability (ΔS/Δt), preservation of biological activity, etc.) and energy indicators (specific energy consumption (Esp), energy utilization efficiency (η_E), average drive load power (N), etc.) [6, 18]. The relationship between these indicators determines the efficiency of the technological mixing cycle, characterizing the degree to which the required technological functions are achieved with minimal energy expenditure.

Integrating the three levels allows the mixing process to be interpreted not as an isolated mechanical operation, but as a holistic cyber-physical system in which material, energy, and information flows interact.

The information subsystem – based on sensor monitoring, digital twins, and IoT platforms – provides feedback between levels, enabling real-time adjustment of technological regimes [14, 19, 20]. This creates prerequisites for adaptive control of the mixing process, improved energy efficiency, and stabilization of mixture quality indicators. The system-based modeling approach makes it possible to formalize cause-and-effect relationships of the type:

$$Y = f(X_m, X_t, P_i), \quad (2)$$

where Y is the resulting process indicators (CV, E_{sp}, $\Delta S/\Delta t$, etc.), X_m represents material properties (physical-mechanical, structural-rheological, chemical-technological, etc.), X_t represents the design and technological parameters of the machines, and P_i denotes the informational–control influences of the system.

The constructed structural-logical model of the feed material mixing process makes it possible to move from a qualitative description of the phenomenon to a quantitative assessment of the influence of individual parameters. On its basis, the factors determining the quality and energy efficiency of the process have been systematized. It has been established that the level of homogenization, specific energy consumption, and structural stability of the mixture depend on the coordinated action of three groups of factors – material, technological, and design [5-7, 11-13, 17, 18].

Material factors (Table 1) characterize the physical-mechanical, chemical-technological, and rheological properties of feed components that determine their flowability, mobility, cohesion, and behavior under shear stress.

Table 1

Key material factors

№	Factor name	Designation	Unit of measurement	Brief description
1	Bulk density	ρ	$kg\cdot m^{-3}$	Characterizes the packing density of particles and determines the inertia of flows
2	Angle of repose	φ	°	Determines the material's flowability and influences the rate of self-settling and circulation
3	Moisture content	W	%	Causes particle adhesion and changes in rheological properties
4	Mean particle size	d_{50}	Mm	Affects mixture homogeneity and the rate of diffusive mixing
5	Coefficient of friction	μ	-	Determines shear conditions and the nature of contact interactions
6	Dynamic viscosity	η	Pa·s	Determines resistance to movement in liquid and viscoplastic media (molasses, high-moisture beet pulp)
7	Yield shear stress	τ_0	Pa	Defines the moment when the material transitions from a state of rest to flow
8	Cohesion	c	$N\cdot m^{-2}$	Determines the particle-to-particle bonding force, which affects the achievement of homogeneity
9	Fiber content	X_{fib}	%	Determines fiber stiffness and elasticity, influencing shear deformation behavior and circulation of fibrous mass
10	Acidity (pH) of the medium	pH	-	Influences the stability of organic components and interaction with metal elements of the mixer (corrosive activity)

Technological factors (Table 2) characterize the operating modes of the machines, which determine the kinematic behavior of material flows within the working volume, the mixing intensity, and the energy distribution within the mixing system, all of which directly affect the quality and energy efficiency of the process. Design factors (Table 3) encompass the geometric parameters and configuration of the working elements, which determine the structure and direction of flows within the mixing chamber, the intensity of shear deformations, and the efficiency of energy transfer from the drive to the working medium, thereby influencing the homogeneity and energy efficiency of the mixing process.

Table 2

Key technological factors

№	Factor name	Designation	Unit of measurement	Brief description
1	Angular velocity of the working element	ω	s^{-1}	Determines the intensity of shear and material circulation within the flow
2	Mixing duration	t	s	Directly affects the achievement of homogeneity but has an inverse effect on energy efficiency
3	Hopper filling degree	ψ	-	Determines flow stability and prevents the formation of stagnant zones
4	Sequence of component loading	-	-	Influences initial stratification and final mixture homogeneity
5	Component feeding rate	Q	kg/s or m^3/s	Determines the mass flow of material into the mixer and affects dosing uniformity, filling degree, energy consumption, and mixture homogeneity
6	Shear rate (deformation gradient)	$\dot{\gamma}$	s^{-1}	Determines the energy required to break the material's cohesive bonds
7	Mechanical Reynolds number	Re_m	-	A generalized indicator of the influence of rheological and technological parameters that characterizes the flow regime (laminar, transitional, turbulent)
8	Ambient temperature	T	°C	Affects the viscosity and cohesion of moist feeds, especially in the presence of molasses or beet pulp
9	Relative height of the mixture layer	h/H	-	Determines the circulation depth and the intensity of axial material exchange
10	Linear velocity of material movement along the mixer axis	v_m	m/s	Characterizes the intensity of axial particle transport and determines the residence time of material in the mixing zone

The presented list of factors is not exhaustive, as the structure of the mixing process is multi-parametric and may vary depending on the type of mixing equipment (auger, paddle, planetary, vibratory, etc.), operating conditions, and the technological purpose of the process – preparation of dry, moist, liquid, or combined feed mixtures, preliminary grinding, or component conveying.

Within the design group, not only dimensional parameters (D, s, β, α, φ_s, δ_l, etc.) are decisive, but also the configurational features of the working elements – the shape of the auger flights (constant, variable, combined), blade profile, bottom geometry (flat, conical, spherical), and the presence of additional elements such as cutting knives, deflectors, guide plates, inserts, or baffles. Such morphological and functional differences in designs are difficult to formalize in tabular form; therefore, analytical methods for evaluating design solutions are advisable, particularly comparative analysis of typical configurations of working elements and mixer layouts, which allows identifying the advantages and limitations of different engineering solutions. These features determine the spatial structure of the flows, the intensity of shear deformations, and the local energy losses within the working volume.

Therefore, they require in-depth experimental analysis and numerical experimentation using CFD or DEM modeling, which makes it possible to quantitatively assess their influence on process homogeneity and energy efficiency and to use the obtained results for optimizing adaptive mixing modes in Smart Feeding technological systems [6, 11, 17-19].

When evaluating mixing efficiency, it is advisable to consider qualitative and energy indicators as interrelated characteristics of the "machine–material–process" system. Qualitative indicators reflect the structural and functional state of the obtained feed mixture and represent the final outcome of the interaction among material, technological, and design factors [6, 17, 18]. Energy indicators determine the efficiency of the mixing process and characterize the conversion of drive energy into useful mechanical work within the machine's working volume, reflecting the level of energy savings and overall system performance [11, 12, 18].

Table 3

Key design factors

№	Factor name	Designation	Unit of measurement	Brief description
1	Diameter of the auger or working element	D	M	Determines the geometric volume of the mixing zone, the axial movement speed of the material, and the resisting torque. Increasing D increases productivity but also raises energy consumption.
2	Spiral (flight) pitch of the auger or blades	s	m	Determines the intensity of axial material transport: a smaller s results in more intensive mixing but higher specific energy consumption.
3	Inclination angle of the flights or blades relative to the horizontal	β	°	Determines the direction and speed of axial particle transport, influencing the structure of circulation flows and shear deformations in the material mass.
4	Inclination angle of the bottom or hopper cone	α	°	Forms the flow direction in the base zone. Optimizing α reduces stagnant zones and ensures uniform material discharge.
5	Bottom curvature radius	R	m	Determines the recirculation conditions of the flow near the lower part of the hopper.
6	Number and arrangement of blades, flights, or ribbons	n	-	Influences the flow structure and circulation stability.
7	Distance between flights (clearance between blades and the wall)	δ_l	m	Determines the nature of material interaction with the mixer walls and the level of hydrodynamic or rheological flow resistance.
8	Installation angle of guide blades (deflectors)	φ_s	°	Defines the geometry of circulation flow direction within the mixer's working volume.
9	Length of the working element	l_k	m	Determines the active mixing zone front and the amount of material simultaneously involved in the process.
10	Volume of the working chamber	V_k	m^3	Determines the overall capacity of the mixer.

For the quantitative determination of these indicators, various assessment methods are used, differing in the nature of the measured parameters, accuracy, labor intensity, and suitability for practical application under production conditions. Based on an analysis of modern scientific and technical practice, four main groups of methods for obtaining, interpreting, and evaluating information on the efficiency of the mixing process can be identified [5-7, 11, 12, 14-20]:

1. Physico-chemical methods are based on determining the concentration of individual components of the feed mixture in control samples using chemical, spectrophotometric, or electrical conductivity analysis. They provide a direct assessment of the degree of homogeneity using statistical criteria – the coefficient of variation (CV) or the standard deviation of concentration (σ). Despite their high accuracy, these methods are labor-intensive and poorly suited for operational control in production environments [17, 18].
2. Physico-mechanical methods are based on measuring indirect physical parameters of the mixture (density, moisture content, electrical conductivity, magnetic susceptibility, color, etc.) that correlate with the level of homogeneity and other qualitative indicators of the mixture. These methods are effective for operational process control and for developing empirical or regression mixing models; however, they require individual calibration for each type of feed material [11, 12].
3. Energy-based methods rely on measuring electrical and mechanical drive parameters (current, voltage, torque, rotational speed), from which power, specific energy consumption (E_p), and energy utilization efficiency (η_e)

are calculated. These indicators reflect the relationship between mechanical load and mixing degree, enabling dynamic evaluation of process efficiency [6, 11, 18]. The obtained data are used to select rational mixer operating modes and design energy-efficient machine configurations.

4. Digital (intelligent-modeling) methods combine Smart Feeding sensor systems, digital twin technology, and numerical process simulation (CFD, DEM, FEM). They provide a comprehensive assessment of qualitative and energy indicators of the mixing process in both real and simulated environments. CFD models enable analysis of velocity distributions, pressure fields, turbulence zones, and shear energy within the working volume, while DEM models track particle trajectories, collision frequency, and residence time in the active mixing zone [12, 17, 19]. Integration of numerical modeling with sensor systems and machine controllers (e.g., by Trioliet, Jaylor, Siloking) forms the basis for adaptive control of mixing modes, helping reduce energy consumption and increase stability of mixture quality indicators [15, 16, 20].

A comprehensive evaluation of mixing efficiency is based on analyzing the relationship between qualitative and energy indicators, which reflect mixture homogeneity, structural stability, and rational use of drive energy. For formalized comparison of different conditions and machine types, it is advisable to use a system of generalized criteria that encompasses the main qualitative and energy indicators of the process (Table 4).

Based on the criteria presented in Table 4, a system for the quantitative evaluation of mixing process efficiency is formed, providing the possibility of a comprehensive analysis of feed mixture quality and the energy rationality of their preparation. The selected indicators combine micro- and macro-level characteristics – from local component uniformity (CV, σ) to integral energy parameters of the process (E_p, η_e) and the stability of the resulting structure (K_s). Such an approach makes it possible to simultaneously assess the degree of homogeneity, the efficiency of energy transfer, and the stability of the technological result over time, which is a necessary condition for optimizing mixing modes and increasing the energy efficiency of feed-preparation systems [6, 11, 12, 17, 18].

A systematic analysis of scientific sources and patent-technical information has shown that despite the significant number of studies in the field of feed preparation and mixing machinery, there are substantial scientific and methodological gaps that limit the possibilities for improving the efficiency of these processes under production conditions. Existing models mostly describe individual elements of the system – flow kinematics, energy consumption, or partial quality indicators of the mixture – without comprehensively considering the interaction of design parameters, operating modes, and the physical-mechanical properties of the material [6; 11; 12; 17–18].

A systematic analysis of scientific and patent-technical sources has demonstrated that, despite numerous studies on the development and improvement of agricultural machinery for feed preparation and mixing processes, key scientific and methodological problems related to the comprehensive evaluation of process efficiency remain unresolved. Most known models describe only separate aspects of the system, in particular flow kinematics, energy consumption, or mixture quality indicators, without a formalized consideration of the interdependence among design parameters, mixer operating modes, and the physical-mechanical properties of feed materials. Existing approaches do not provide a generalized description of the "machine–material–process" system, which limits the possibilities for optimizing designs and developing adaptive energy-efficient mixing modes [6, 11, 12, 17–18].

Within the material subsystem, the influence of the structural–rheological properties of feed materials – yield stress (τ_0), effective viscosity (η_e), cohesion (c), dry matter content (W), and particle-size characteristics (d_{50}) – on the mixing kinetics and the formation of the spatial flow structure within the mixer's working volume remains insufficiently studied. For most multicomponent feeds, a generalized rheological classification is lacking, which complicates the parameterization of materials during CFD and DEM modeling of mixing processes [8, 9, 11, 12].

In the energy subsystem, modern research focuses mainly on studying the influence of individual geometric parameters (flight inclination angle β, spiral pitch s, guide-blade installation angle φ_s, hopper filling coefficient ψ) and kinematic characteristics (rotational speed n, process duration t) on specific energy consumption E_p. At the same time, generalized models that would systematically account for the combined action of these factors together with the rheological properties of feed materials (yield stress τ_0, effective viscosity η_e, cohesion c) are absent. This limits the possibility of establishing universal relationships among design parameters, operating modes, and energy efficiency indicators (η_e, Kd), which is a necessary prerequisite for developing adaptive control systems for energy-efficient mixing modes [6, 11, 12, 18].

In the information subsystem, there is insufficient integration of Smart Feeding sensor technologies capable of providing real-time multiparametric monitoring of technological processes – drive load, current consumption, moisture content, temperature, density, and other characteristics of the material flow – while simultaneously reflecting their influence on mixture quality indicators (CV, σ, K_s). The absence of formalized methods for correlating these parameters with homogeneity and energy-efficiency indicators limits the development of adaptive control systems that account for process time dynamics, the rheological behavior of the material, and the structural–kinematic features of mixers [15, 16, 20].

Table 4

Main criteria for evaluating the quality and energy efficiency of the feed mixing process

№	Criterion name	Designation	Unit of measurement	Physical meaning and interpretation	Informative value and applicability limits
1	Coefficient of variation of concentration	*CV*	%	Characterizes the statistical non-uniformity of component distribution within the mixture	Suitable for laboratory and production control, but requires representative samples
2	Standard deviation of concentration	σ	%	Determines the degree of deviation of component concentrations from the mean value	Used together with CV; less sensitive to local fluctuations
3	Homogeneity index	*H*	-	Reflects the convergence of component distributions by spatial coordinates or fractional composition	Used in DEM and CFD modeling; requires digital data processing
4	Fractional uniformity coefficient	*Kf*	-	Determines the uniformity of particle-size distribution	Informative for bulk feeds but does not reflect chemical uniformity
5	Mixture structure stability coefficient	*Ks*	-	Indicates the preservation of mixture uniformity over time after mixing	Important under production conditions; requires dynamic observations or sensor-based monitoring
6	Adaptive control coefficient	η_a	-	Determines the system's ability to adjust mixing modes	Used in Smart Feeding / Digital Twin systems; requires sensor monitoring
7	Specific energy consumption of the process	E_p	kW · h/ t	Amount of energy consumed per unit mass of mixed material	Generalized characteristic of energy efficiency
8	Energy utilization efficiency	η_e	-	Ratio of useful mechanical work (mixing) to total consumed energy	Used in energy analysis of processes; determined experimentally or by numerical methods
9	Instantaneous drive power	*P(t)*	kW	Time-dependent power variation throughout the mixing cycle	Enables analysis of energy consumption dynamics; used for constructing energy graphs
10	Mixing energy coefficient	$Ke = E_p/CV$	kW · h/ (t·%)	Integral indicator combining energy and quality characteristics	Informative for comparative analysis of machines or modes; requires accurate measurement of CV
11	Specific power per unit mass of the mixture	$N_p = P/m$	kW /t	Indicates the intensity of energy action on the material within the working volume	Applied in testing machines with different capacities
12	Dynamic load stability coefficient	$Kd = \sigma_p/\bar{P}$	-	Ratio of the root mean square deviation of instantaneous power to its mean value	Used to assess the uniformity of drive load; informative when transitioning to automated control

From a methodological standpoint, modern approaches to the design and optimization of mixer construction and operating modes remain predominantly empirical, with a limited level of generalization of regularities and a low degree of formalization of mechanical-technological processes. Most existing models lack a comprehensive description of the interrelationships among the geometric parameters of working elements, operating modes, and the rheological characteristics of feed mixtures, which prevents accurate prediction of mixing efficiency when changing equipment scales and types. CFD and DEM modeling methods provide deep reproduction of local flow kinematics and particle microdynamics; however, in most studies, their comprehensive experimental verification is lacking. Moreover, the scale effect when transitioning from laboratory to industrial systems remains insufficiently studied, which limits the reliability of practical application of the results [17, 19].

Thus, further advancement of research on the mixing process in the context of analyzing structural parameters and mixer operating modes constitutes an important scientific and practical task aimed at forming generalized mechanical-technological regularities of the process. Its solution requires the integration of experimental, numerical, and energy-based research methods capable of adequately reproducing real machine operating conditions. Special attention should be paid to the systematic generalization of results related to the optimization of structural–operational correlations and the formalization of relationships among geometric parameters, operating modes, and material properties, which will create scientific preconditions for developing adaptive energy-efficient operating modes for next-generation mixers [6, 11, 12, 14–20].

The generalization of the results of the conducted system analysis indicates that the efficiency of the feed mixing process is determined by the coordinated interaction of the material, energy, and information subsystems of the technological process. It has been established that mixture quality and energy consumption levels depend on a combination of physical-mechanical and rheological properties of the material, structural features of the working elements, and the parameters of the technological regime. Existing approaches to evaluating process efficiency remain fragmented, focusing mainly on individual groups of factors, whereas the development of integral criteria that comprehensively account for the interaction within the “machine–material–process” system is a necessary prerequisite for the further optimization of mixer designs and operating modes. The obtained generalizations form the theoretical and methodological basis for the next stage of research, aimed at modeling the mechanical-technological regularities of the process and developing principles of energy-efficient control of mixing regimes under production conditions.

5. Conclusion

The conducted research made it possible to systematically substantiate the place of the mixing process within the feed preparation technological chain and to determine its key role in ensuring stable feed mixture quality and increasing the energy efficiency of technological systems. The developed structural-logical model of the process, which integrates the material, energy, and information subsystems, reflects the cause-and-effect relationships among the physical–mechanical properties of feed materials, machine design parameters, and technological operating modes.

The factors that determine the quality and energy efficiency of mixing have been systematized and classified according to the nature of their influence – material, technological, and design-related. Based on an analysis of methods and criteria for evaluating process efficiency, a system of indicators has been formed that reflects mixture homogeneity, structural stability, and the rational use of drive energy. The identified scientific and methodological gaps indicate the need to develop mechanical-technological models that comprehensively account for the interactions within the “machine-material-process” system. The results of the study form a methodological foundation for improving mixer designs, optimizing their operating modes, and implementing energy-efficient control principles for the mixing process under production conditions.

Further research should focus on developing and verifying numerical models (CFD, DEM) of the feed mixing process, taking into account the rheological properties of materials and the geometry of working elements. It is also important to develop algorithms for adaptive control of technological mixing parameters based on sensor monitoring within the Smart Feeding environment, which will enhance energy efficiency and reproducibility of results in industrial applications.

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СИСТЕМНА МОДЕЛЬ ПРОЦЕСУ ЗМІШУВАННЯ МАТЕРІАЛІВ У ТЕХНОЛОГІЧНОМУ ЛАНЦЮЗІ КОРМОПРИГОТУВАННЯ

У статті проаналізовано місце процесу змішування кормових матеріалів у технологічному ланцюзі кормоприготування та його роль у забезпеченні стабільної якості кормових сумішей і підвищенні енергоефективності машин сільськогосподарського призначення. Метою дослідження є системне узагальнення факторів, методів і критеріїв оцінювання ефективності процесу змішування, а також виявлення науково-методологічних прогалин, які обмежують подальший розвиток конструкцій і режимів роботи кормозмішувачів. У роботі застосовано методологію системного аналізу, механіко-технологічного моделювання та порівняльно-аналітичний підхід до оцінки ефективності процесів. Проведено узагальнення наукових і патентно-технічних джерел, проаналізовано сучасні рішення у сфері конструкцій вертикальних змішувачів і методів оцінювання їх ефективності. Сформовано структурно-логічну модель процесу змішування, яка включає три взаємопов'язані підсистеми: матеріальну, енергетичну та інформаційну. В межах моделі виділено три рівні взаємодії: вхідні параметри (властивості матеріалів), керувальні впливи (режими та конструктивні параметри машин) і результати процесу (якісні та енергетичні показники). Узагальнено класифікацію факторів, що визначають ефективність змішування, за трьома групами – матеріальними, технологічними й конструктивними, із зазначенням ключових параметрів і критеріїв впливу.

Проаналізовано методи оцінювання ефективності змішування: фізико-хімічні, фізико-механічні, енергетичні та цифрові (інтелектуально-моделювальні). Наведено узагальнені критерії оцінки якості суміші та енергоефективності процесу. Виявлено, що існуючі підходи залишаються фрагментарними й не враховують комплексно взаємодію системи «машина – матеріал – процес». Обґрунтовано необхідність розроблення механіко-технологічних моделей змішування з урахуванням реологічних властивостей кормових матеріалів, параметрів робочих органів і режимів роботи машин. Підкреслено перспективність використання чисельних методів CFD та DEM разом із сенсорними системами Smart Feeding для реалізації адаптивного керування процесом у реальному часі.

Отримані результати формують теоретико-методологічну базу для подальших досліджень, спрямованих на оптимізацію конструкцій кормозмішувачів, зниження питомих енерговитрат і підвищення стабільності якості сумішей у виробничих умовах.

Ключові слова: *кормозмішувач, змішування кормів, якісні та енергетичні показники, фактори впливу, механіко-технологічна система, структурно-логічна модель, системна модель, критерії оцінки процесу.*

Ф. 2. Рис. 2. Табл. 4. Літ. 20.

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