Agrarian Bulletin of the Black Sea Littoral. 2025, Issue 116
ISSN2707-1162 (online) ISSN 2707-1154 (print)
DOI 10.37000/abbsl.2025.116.11
UDC 636.085.55.4

Igor Dudarev,
Candidate of Technical Sciences, Associate Professor
of the Department of Agroengineering,
Odesa State Agrarian University, Odesa, Ukraine
ORCID ID: 0000-0001-9509-6970
e-mail:247531@ukr.net

Serhii Uminskyi,
Candidate of Technical Sciences, Associate Professor
of the Department of Agroengineering,
Odesa State Agrarian University, Odesa, Ukraine
ORCID ID: 0000-0002-7767-8405
e-mail:ymoshi@ukr.net

Inna Moskalyuk,
Candidate of Technical Sciences, Associate Professor
of the Department of Information Technologies,
Odesa State Agrarian University, Odesa, Ukraine
ORCID ID: 0000-0002-3421-4029
e-mail: inna4406@ukr.net

Serhiy Zhitkov,
Associate Professor, Department of Agricultural Engineering,
Odesa State Agrarian University , Odesa, Ukraine
ORCID ID: 0000-0003-0598-9906
e-mail: sergejzitkov1983@gmail.com

OXYGEN SORPTION IN COMBINED FEEDS DURING STORAGE

Abstract

One of the primary vectors for the development of enterprises in the compound feed industry is to solve urgent tasks related to improving technologies and methods aimed at optimising the use of raw materials, improving their quality, increasing yields and expanding the range of finished products suitable for long-term storage. The quality of compound feed during storage largely depends on its physical properties, chemical composition, characteristics of its components, their uniform distribution in the mixture, the presence of antioxidants, production technology, and storage conditions.

At the same time, the complex influence of these factors on the duration of storage has not yet been sufficiently studied and systematised. It is important to establish the optimal storage period, since the economic losses of feed components when this period is exceeded are unjustified. In view of this, it is becoming increasingly important to study the interrelated processes of mixing and storage, which will allow determining the patterns of changes in the quality of compound feed at

minimum cost. As part of this study, it is necessary to assess the impact of mixture homogeneity on the storage efficiency of bulk feed, which is of significant scientific and technical importance. There is an urgent need to develop a number of scientific approaches, including:
- establishing patterns of changes in the qualitative characteristics of feed mixtures depending on chemical compounds and physical properties;
- determining an indicator for assessing the uniformity of feed component distribution in the mixture;
- studying the formation of homogeneous mixtures in relation to the physical properties of components, their composition, mixing duration, and parameters of the continuous mixing process;
- developing a methodology for determining feed component losses during storage;
- justification and selection of a comprehensive criterion for assessing the effectiveness of compound feed storage, taking into account the total cost of compensation for losses.

The article proposes a generalised model that effectively describes the process of oxygen sorption as a function of two variables.

Keywords: *compound, feed, process, oxygen, change, sorption.*

Introduction. Verification of the characteristics of changes in the condition of compound feed during storage, taking into account the homogeneity of the mixture.

Problem statement, analysis of current studies. Modern principles of animal feeding impose strict requirements, emphasising a multifactorial approach to meeting their nutritional needs. Diets must not only meet performance indicators, but also take into account the general conditions of animal husbandry. Meeting these requirements involves maintaining health, strict control of feed quality and safety, as well as their economic efficiency in use. To achieve these goals, producers and farmers have a wide range of options available to them, including various categories of feed. It should be noted that there is a significant difference between basic feeds, which are the staple component of the diet, and concentrated feeds, which serve as an additional source of nutrients. Of particular importance is the production of compound feeds, which plays a key role in the pig farming industry.

Purpose of the study: The uniformity and quality of feed mixtures are critically important for both large agro-industrial complexes and small farms. An efficiently organised mixing process ensures uniform distribution of nutrients in feed, which has a positive effect on animal productivity, their physiological condition and overall welfare. In addition, this factor directly affects the economic viability of production. Deficiencies or violations of mixing technology can cause significant complications, such as reduced feed efficiency, uneven distribution of nutrients, and a corresponding drop in productivity. This ultimately has a negative impact on the financial performance of the industry, jeopardising its profitability and sustainable development. The study presented in this paper aims to examine the main factors that determine the feed mixing process and analyse their impact on the functioning of production enterprises and farms. The high quality of pig feed largely depends on a carefully formulated diet that takes into account the individual nutritional needs of animals at each stage of their development.

Presentation of the main material. At the same time, an inefficient mixing process can significantly reduce the usefulness of the recipe due to the segregation of ingredients. This phenomenon negatively affects the absorption of nutrients, leading to a deterioration in the overall health of animals. In contrast, properly organised mixing of compound feed ensures an even distribution of nutrients, which has a positive effect on the productivity, physiological condition and welfare of pigs. Thus, the stability and high quality of the feed mixing process is a strategic factor for optimising production results and strengthening economic sustainability. An efficiently organised technological process allows the creation of balanced and nutritious diets that contribute to increased productivity and improved overall functioning of livestock farms.

Inadequate feed mixing can cause an imbalance of nutrients, which will negatively affect animal health and lead to increased maintenance costs. To address these issues, it is important to implement strategic measures such as investing in modern mixing equipment, regularly training staff, and systematically monitoring the quality of technological processes. These actions ensure the stable development of the industry and maximum economic efficiency for all participants in the production chain. At first glance, the creation of compound feed may seem like a simple process of mixing several separate ingredients. However, in practice, compound feed is a complex product that includes a variety of components and often special additives.

Its production is based on decades of scientific research, technological development and practical experience of specialists. The specifics of compound feed formulation, taking into account the type and age of animals, involves the creation of homogeneous mixtures that ensure a balance of biologically active substances. This is especially important for components, an excessive amount of which can harm the body, making technological precision and perfection of the process critically important [3, 4, 9, 10]. Scientific research confirms the significant advantage of using compound feed with uniform distribution of components for animal feeding. High feed homogeneity contributes to a stable supply of essential nutrients, which has a positive effect on animal productivity, their overall health and the quality of the final product. Insufficient homogeneity of mixing can lead to a number of problems, such as reduced feed efficiency, slow growth and deterioration of product characteristics.

That is why control of this parameter is critically important for modern feed production. The homogeneity of compound feed mixing is considered one of the key quality indicators that directly affects the efficiency of feeding and nutrient absorption. This factor is influenced by the following aspects: mixer design, technological parameters of production processes, and characteristics of raw materials. Increasing the level of homogeneity contributes to the stability of nutrition, optimal absorption of nutrients and increased animal productivity. It has been proven that low feed homogeneity causes uneven distribution of such important elements as phosphorus and calcium, which inhibits the development of the skeletal system and overall growth of animals. A deficiency of certain groups of vitamins in the diet can cause serious metabolic disorders, resulting in vitamin deficiency in animals and birds.

Uneven distribution of trace elements and salts in the feed also causes negative chemical reactions, including vitamin inactivation. In this process, oxygen in the pores between feed particles plays a decisive role. When direct contact between trace elements and vitamins is minimised, the quality and effectiveness of the feed are significantly improved.

Studies on the stability of vitamins in premixes show that their shelf life increases with the homogeneity of the mixture. However, the exact pattern of stability changes has not yet been established. It has been found that the size of microcapsule particles significantly affects the degree of homogeneity. According to researchers, the size of these particles should be determined depending on the amount of microcomponents added to the feed, especially in cases involving biologically active substances.

The physical properties of feed are also important for its shelf life and for the level of oxygen absorption in mixtures with different recipes. The most important characteristics include friction properties, which are determined by both external and internal friction coefficients, particle size distribution, density, bulk density, settling, hygroscopicity, thermal conductivity, gas permeability, porosity between particles, and the volume of the spaces between them. The pressure exerted on the mixture of feed components affects a number of indicators, in particular bulk density and shelf life as the main factors. Bulk density during free filling depends on the method of packaging bulk materials and tends to decrease during the grinding process. In the context of the physical and mechanical properties of bulk materials, the relationship between volume and mass reveals a fundamental pattern: as volume increases, mass decreases, and vice versa. The concept of volumetric space reflects a set of characteristics determined by the arrangement of material particles, their geometric parameters, and the state of the surface layer. Air exchange processes in the pore structure play a decisive role in the behaviour of such systems, particularly in the storage of compound feed, where the level of aerodynamic resistance is influenced by the air flow velocity, which depends on the drilling process. During active ventilation of bulk materials, a significant influence of air volume on the intensity of moisture evaporation has been established. This process is determined by the active surface area of the particles, which indirectly affects water transfer, as well as factors such as the pressure difference between saturated water vapour and vapour in the environment, barometric pressure and the rate of air filtration through the pores. As the moisture content of feed particles increases, drilling power increases, leading to a decrease in material weight and an increase in the natural rebound angle.

Experimental studies have also shown that adding fat to compound feed helps reduce moisture absorption and lower the internal friction coefficient, while also having a positive effect on the volume of the material. Conversely, the addition of molasses in small quantities causes increased moisture absorption, an increase in the internal friction coefficient and the angle of natural rebound, but at the same time reduces the bulk density and density of the bulk material. The dependence of the equilibrium moisture content of the feed mixture on the relative humidity at different storage temperatures was mathematically described using empirical formulas in the form of second-degree polynomials. Since for fixed temperatures of 0°C and 10°C the coefficients in the polynomial expressions are the same when the function values are distributed over two eccentric curves of 0.25%, the empirical correlation obtained is:

$$W_P = 11{,}11 - 0.19\varphi + 0.004\varphi^2 \quad (1)$$

Within the scope of the study, the moisture content of pig feed was analysed after spraying under conditions of specific relative air humidity values: 20%, 60%, 80% and 100%. The parameters were obtained based on experimental measurements. Extreme values of equilibrium moisture content, which varied depending on the duration of feed storage, were determined for each specified relative humidity level by differentiating the empirical dependencies given in previous research works [3, 7, 10].

The results of the calculations show that at a relative air humidity of 20%, the time to reach a state of equilibrium moisture W_P = 7.42% is eight days. However, the authors' claim that equilibrium moisture is reached in four days was not confirmed. It has been established that when feed is stored for four days, the equilibrium moisture level reaches 86.6%. If the relative air humidity is $f \geq 100\%$, the authors report that the process of reaching moisture equilibrium is completed within 15 days [3, 5].

A key aspect of ensuring the quality characteristics of compound feed during long-term storage is the intensity of moisture exchange between the two-phase system consisting of feed and the environment (air). Based on the experimental data obtained, a stable sorption rate at f = 100% and moisture desorption at f = 20% was established. The dynamic analysis allowed us to identify patterns of sorption and desorption variations, which demonstrate high activity of these processes during the first four days with a gradual decrease in their intensity over time. The duration of storage of compound feed without significant deterioration in its quality characteristics is largely determined by gas exchange conditions, which in turn depend on the porosity of the product. Analysis of studies [3, 8, 10] shows that elevated temperatures and high gas permeability of loose feed promote the intensification of oxidative processes. During the processing of experimental data, mathematical dependencies were formulated for the intensity of oxygen sorption by different feed compositions, taking into account their initial moisture content and storage duration of 15, 30 and 45 days. A summary of the experimental results demonstrates significant changes in gas exchange indicators. By the end of the storage period, oxygen absorption and carbon dioxide release in all studied feed variants had increased significantly, exceeding the initial values regardless of the initial moisture content.

Based on the analysis of the data, the optimal moisture content of compound feed, which ensures maximum storage life, was determined to be 0.5%. Experiments also showed that compound feed with a high content of finely dispersed components of plant and animal origin is characterised by increased gas exchange, which creates favourable conditions for the reproduction of microorganisms. In addition, the fat component and microadditives in the recipe mixtures have an additional effect on the activation of microflora development — this effect is stronger compared to other compositions. To analyse the effect of microorganisms on the intensity of gas exchange processes, comparative studies were conducted using sterile and non-sterile products [1, 5, 7]. The results show significant differences, which allows us to conclude that microflora plays a critical role in determining the overall quality of compound feed during long-term storage. At the end of the storage period, it was found that the gas exchange rate in unsterilised feed was significantly higher than in sterilised feed – several times higher. Taking this fact into account, the researchers suggested that the low intensity of gas exchange in feed stored at reduced positive temperatures is due to the absence of microbial growth. This approach makes it possible to extend the shelf life of the product without significantly changing its properties.

In a mixture of compound feed mills with high moisture content and active microorganisms, carbohydrate gas desorption intensifies and exceeds the invasiveness of grain mixtures before crushing several times over.

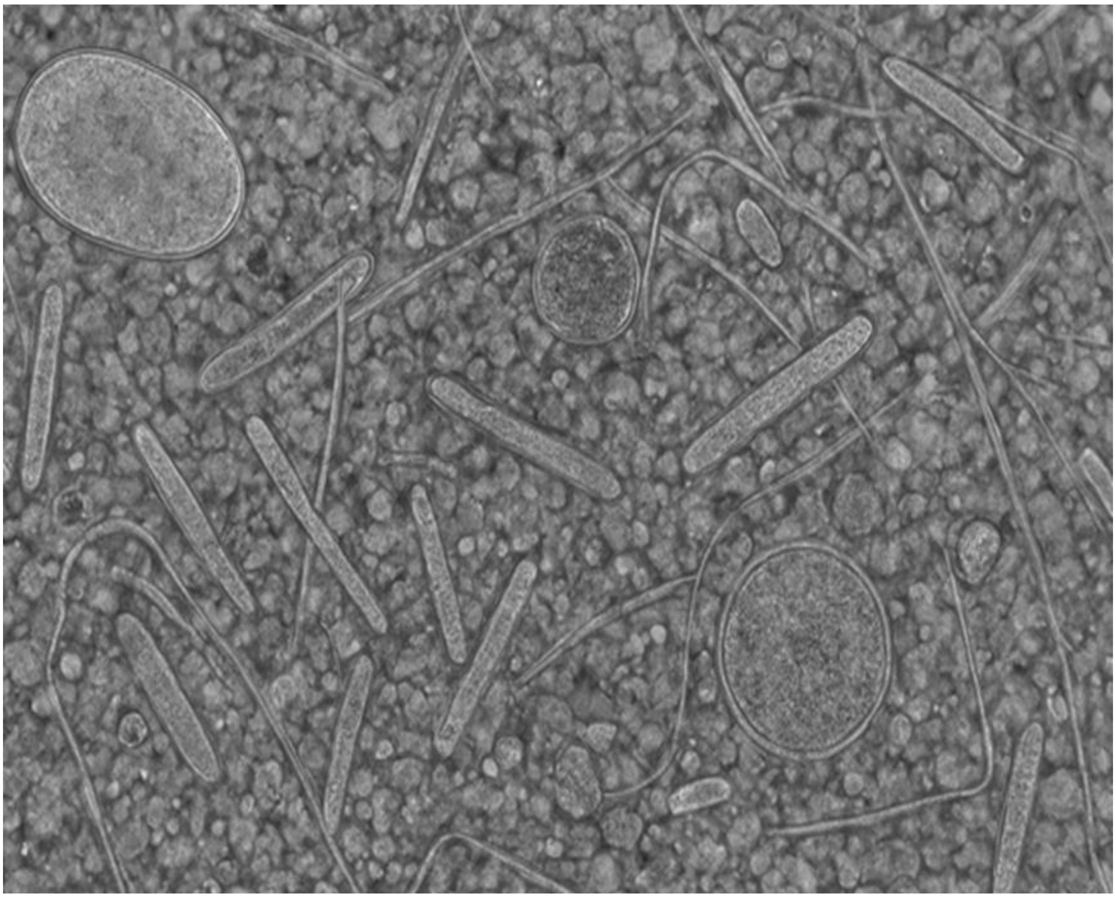

Fig. 1. Volumetric space and microorganisms in compound feed (Bacillus, Enterobacter, Lactobacillus, Saccharomyces, Aspergillus, Penicillium, Fusarium) [7, 9].

Table 1.

Main types of microorganisms in compound feed

Group of microorganisms	Examples of genders	Cell shape / appearance	Impact on compound feed
Lactic acid bacteria	Lactobacillus, Enterococcus	Rod-shaped, short	Can maintain quality, inhibit the growth of pathogens

Spore-forming bacteria	Bacillus, Clostridium	Long rods, sometimes with spore formation	Some are beneficial (probiotics), others spoil feed
Pathogenic bacteria	Salmonella, E. coli (деякі штами)	Rod-shaped	Cause diseases in animals, dangerous
Yeast	Saccharomyces, Candida	Oval/round cells, budding	Partially useful (improve fermentation), sometimes spoil feed
Mould fungi	Aspergillus, Penicillium, Fusarium	Thread-like mycelial structures, spores	Main sources of mould and mycotoxins
Actinomycetes	Streptomyces	Thread-like, mushroom-like	Cause a musty smell and spoilage of feed

The results of mathematical analysis of experimental data concerning changes in the intensity of carbon dioxide release from compound feed produced according to specified recipes were evaluated at different moisture levels.
W = 10.5... (Δ - vitamin A, ● - vitamin B, O - vitamin B2) and storage time = 30.45 s, represented by empirical expressions in the form of second-degree polynomials.

$$I = A+bw+cw^2 \qquad (2)$$

Table 2.

Values of coefficients to I=a+bw+cw² during storage for 30 days

Combined recipe	Indicators	Moisture content,% (30 days of storage)	Coefficients At indicators t = 22.5 ±2.50C		
			a	вв	c
DSTU 4124, recipe No. SK-21	Δ	10,5 - 15,5	6583,7	1132,6	48,6
	●		102,7	21,5	1,21
	O		2166,4	369,8	15,7

Table 3.

Values of coefficients to $I=a+bw+cw^2$ during storage for 45 days

Combined recipe	Indicators	Moisture content, % (45 days of storage)	Coefficients At indicators t = 22.5 ±2.50C		
			a	вв	c
DSTU 4124, recipe No. SK-21	Δ	10,5 - 15,5	6583,7	1132,6	48,6
	●		102,7	21,5	1,21
	O		2166,4	369,8	15,7

Observations show that when porosity is in the range of 55-58%, the ability of crushed compound feed to transfer heat is significantly reduced. If compound feed is stored at low temperatures, its low thermal conductivity helps to maintain a low temperature for a long time. This justifies the possibility of extending the storage period in winter without significantly affecting quality. The interaction of changes in the biological and physical characteristics of feed, enhanced by the respiratory activity of microorganisms, combined with the low thermal conductivity of the mixture, leads to self-heating of the product, which gradually leads to its complete destruction. The results of laboratory experiments measuring J-oxygen sorption for SK-21 feed, conducted over 30 days at a stable temperature of 22.5 °C and controlled humidity, allowed us to derive certain empirical relationships in the form of second-order polynomials. Based on this, a general empirical equation was formulated, which allows calculating oxygen sorption as a function of two variables.

$$J= - 2447,3 +383,1 w - 13,3w^2 + 306,65 \tau_x - 41,4 w \tau_x +1,2 w^2+ 13,1 \tau_x^2- 2,86 w \tau_x^2 + +0,15 w^2 \tau_x^2 \quad (3)$$

A generalised empirical expression of the dependence of oxygen sorption in the storage of compound feed for fattening pigs according to the recipe has been obtained.

$$J=-2646,9 +393w -13,75 w^2 - 427,7 \tau_x + 81,08 w \tau_x -3,72 w^2 \tau_x +33,07 \tau_x^2-5,92 w \tau_x^2+0,26 w^2 \tau_x^2 \quad (4)$$

sorption during storage at a constant temperature and variable humidity within the range of 10.5...15.5%.

Conclusions and prospects for further research. During the experimental study of the oxygen sorption process by SK-21 compound feed for 30 days under laboratory conditions that simulated a set temperature of 22.5 °C and different humidity levels, empirical sorption dependencies were identified. They are presented in the form of second-degree polynomials.

Using mathematical processing of the obtained data, it was possible to form a generalised empirical model that allows to effectively describe the oxygen sorption process depending on two variables. The results of the analysis of the experiments showed that the shelf life of brittle compound feed largely depends on the physical characteristics of the mixture, the dynamics of moisture exchange, as well as the parameters of oxygen sorption and carbon dioxide desorption.

These characteristics can be calculated within the framework of an empirical model. The overall picture of gas exchange processes in compound feed allows us to conclude that an increase in humidity and temperature of the environment contributes to the activation of sorption and desorption processes, creates favourable conditions for the development of microorganisms and, at the same time, leads to a decrease in the quality indicators of feed combinations as the storage period increases.

References

1. Barel S. (2013) Overview of the needs and composition of the feed and harmful substance safety inspection system in Israel's VSAH. Beth Dagan: Veterinary and Animal Health; 154 pp.[in Israel]
2. Brindzia Z. F. , Jula I. O.(2000) System of technologies in crop production. Study guide. Ternopil: Consulting Center. 188 p. [in Ukrainian]
3. Drobat V.Y. (1998) Handbook of bakery production technology Kyiv: Ruslana. 415 pp. [in Ukrainian]
4. Dudarev I.I. (2014) Grain moisture. Agrarian Bulletin of the Black Sea Region, Issue 74, P.129–132. [in Ukrainian]
5. Dudarev I. (2016). Processing and frictional properties of grain. Agrarian Bulletin of the Black Sea Region, Issue 80, P. 137–144. [in Ukrainian]
6. Kaminsky V.D. Babich M.B. (2000) Processing and storage of agricultural products. Odesa: Aspect,. – 459 p. [in Ukrainian]
7. Macrae, R., Robinson K., Sadler M.(2020) Encyclopaedia of Food Science, Food Technology, and Nutrition. Academic Press: New York, 234 p. [in USA]
8. Muller-Harvey I. (2004) Modern methods of feed analysis. A: Evaluation of the quality and safety of animal feed. Rome: FAO; S. 1-34.[in Italy]
9. Piksha G. R., Bondarenko V. (1985) Cereals – K.: Harvest,. 272 p. . [in Ukrainian]
10. O.T. Lisovenka (2000) Technological equipment of bakery and pasta industries. Textbook. /Ed. Academician Kyiv: Scientific opinion, – 181 p. . [in Ukrainian]
11. Technological equipment of bakery and pasta industries. Textbook. /Ed. Academician O.T. Lisovenka. Kyiv: Naukova dumka, 2000 181 pp. . [in Ukrainian]

СОРБЦІЯ КИСНЮ В КОМБІКОРМАХ ПРИ ЙОГО ЗБЕРІГАННІ

Анотація

Одним з першочергових векторів розвитку підприємств комбікормової галузі є розв'язання нагальних завдань з удосконалення технологій та методик, спрямованих на оптимізацію використання сировини, покращення її якості, підвищення врожайності та розширення асортименту готової продукції, придатної до тривалого зберігання. Якість комбікорму в процесі зберігання значною мірою залежить від фізичних властивостей, хімічного складу, характеристик компонентів, рівномірності їх розподілу в суміші, наявності антиоксидантів, технології виробництва та умов зберігання.

Водночас, комплексний вплив цих факторів на тривалість зберігання досі недостатньо вивчений і систематизований. Важливо встановити оптимальний термін зберігання, оскільки економічні збитки кормових компонентів при перевищенні цього терміну є невиправданими. З огляду на це, набуває актуальності вивчення взаємопов'язаних процесів змішування та зберігання, що дозволить визначити закономірності змін якості комбікормів при мінімальних витратах.

У рамках цього дослідження необхідно оцінити вплив однорідності суміші на ефективність зберігання сипучих кормів, що має важливе науково-технічне значення. Існує нагальна потреба у розробці ряду наукових підходів, серед яких:
- *встановлення закономірностей змін якісних характеристик кормових сумішей в залежності від хімічних сполук та фізичних властивостей;*
- *визначення показника для оцінки однорідності розподілу кормових компонентів у суміші;*
- *дослідження формування однорідних сумішей у взаємозв'язку з фізичними властивостями компонентів, їх складом, тривалістю змішування та параметрами технологічного процесу безперервного змішування;*
- *розробка методології визначення втрат кормових компонентів під час зберігання;*
- *обґрунтування та вибір комплексного критерію оцінки ефективності зберігання комбікормів, враховуючи сукупну вартість компенсації втрат.*

У статті запропоновано узагальнену модель, яка ефективно описує процес сорбції кисню як функцію двох змінних.

Ключові слова*: комбікорм, процес, кисень, зміна, сорбція.*

Стаття надійшла до редакції 15 червня 2025 року
Стаття пройшла рецензування 15 липня 2025 року
Стаття опублікована 30 вересня 2025 року