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FUNCTIONAL SIGNIFICANCE OF ORGANIC ACIDS IN ENSURING FEED QUALITY AND METABOLIC HOMEOSTASIS OF FARM ANIMALS

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Abstract. The article summarizes current scientific data on the functional significance of organic acids in ensuring feed quality and maintaining metabolic homeostasis in farm animals and poultry. It has been shown that organic acids, particularly hydroxy acids, play an important role in stabilizing the microbiological condition of feed raw materials, inhibiting the growth of pathogenic and opportunistic microorganisms, and improving the sanitary quality of feed. Owing to their ability to reduce feed pH, they help extend the shelf life of feed and reduce the risk of microbiological contamination. The biological role of organic acids in regulating digestion and energy metabolism is considered. Studies indicate that organic acids can influence the composition and functional activity of the intestinal microbiota, stimulating the production of short-chain fatty acids that perform energy and signaling functions, participate in immune regulation, support intestinal barrier integrity, and are involved in lipid and carbohydrate metabolism. Their role in forming a stable intestinal environment and improving nutrient utilization is demonstrated. The influence of technological parameters of feed production on the efficiency of organic acid use is analyzed. Previous studies indicate that the degree of feed particle size, hydrothermal treatment modes, and the stability of biologically active additives significantly affect their functional activity. Modern technological approaches have been proposed to enhance the effectiveness of organic acid supplementation. The results of studies on the use of organic acids in pig and poultry production are presented. Studies indicate that their use can improve growth performance, enhance feed efficiency, stabilize the intestinal microbiota, and strengthen the immune status of animals. The prospects for their use as a safe alternative to antibiotic growth promoters in modern feeding systems are emphasized.

Key words: *hydroxy acids, intestinal microbiota, short-chain fatty acids, energy metabolism, carbohydrate fermentation, immune reactivity.*

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ФУНКЦІОНАЛЬНЕ ЗНАЧЕННЯ ОРГАНІЧНИХ КИСЛОТ У ЗАБЕЗПЕЧЕННІ ЯКОСТІ КОРМІВ ТА МЕТАБОЛІЧНОГО ГОМЕОСТАЗУ ТВАРИН

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Анотація. У статті узагальнено сучасні наукові дані щодо функціонального значення органічних кислот у забезпеченні якості кормів та підтриманні метаболічного гомеостазу організму сільськогосподарських тварин і птиці. Показано, що органічні кислоти, зокрема гідроксикислоти, відіграють важливу роль у стабілізації мікробіологічного стану кормової сировини, пригніченні розвитку патогенних і умовно-патогенних мікроорганізмів та підвищенні санітарної якості кормів. Завдяки здатності знижувати pH кормового середовища вони сприяють подовженню терміну зберігання кормів і зменшенню ризику їх мікробіологічної контамінації. Розглянуто біологічну роль органічних кислот у регуляції процесів травлення та енергетичного обміну. Встановлено, що вони здатні впливати на склад і функціональну активність кишкової мікробіоти, стимулюючи утворення коротколанцюгових жирних кислот, які виконують енергетичні та сигнальні функції, беруть участь у регуляції імунної відповіді, підтриманні бар'єрної функції кишечника та метаболізмі ліпідів і вуглеводів. Показано їх роль у формуванні стабільного кишкового середовища та підвищенні ефективності використання поживних речовин. Проаналізовано вплив технологічних параметрів виробництва кормів на ефективність використання органічних кислот. Зазначено, що ступінь подрібнення кормової сировини, режими гідротермічної обробки та стабільність біологічно активних добавок істотно впливають на їх функціональну активність. Розглянуто сучасні технологічні підходи, зокрема використання комплексних підкислювачів і мікрокапсульованих форм органічних кислот. Наведено результати досліджень щодо використання органічних кислот у свинарстві та птахівництві. Встановлено, що їх застосування сприяє покращенню ростових показників, підвищенню ефективності використання корму, стабілізації кишкової мікробіоти та зміцненню імунного статусу тварин. Підкреслено перспективність їх використання як безпечної альтернативи антибіотикам-стимуляторам росту у сучасних системах годівлі.

Ключові слова: *гідроксикислоти, кишкова мікробіота, коротколанцюгові жирні кислоти, енергетичний обмін, ферментація вуглеводів, імунна реактивність.*

Introduction. Modern livestock and poultry production operate under conditions of high production intensity, which places increased demands on the quality, safety, and stability of feed. Feed is a key factor that directly determines the productivity, health, immune status, and realization of the genetic potential of animals and poultry. Violations of harvesting, transportation, and storage technologies for feed raw materials contribute to the development of molds and bacteria, as well as to the accumulation of mycotoxins and other toxic metabolites. This can lead to decreased animal productivity, metabolic disorders, immunosuppression, and significant economic losses in the industry.

The issue of microbiological and toxicological stability of feed in animal husbandry and poultry production is becoming particularly relevant in the context of global climate change, which contributes to increased contamination of grain crops with mycotoxin-producing fungi. This necessitates the introduction of effective technological solutions to improve feed preservation, among which natural organic compounds with preservative properties play an important role (Pearlin et al., 2020).

In this context, various organic acids, including hydroxy acids, which represent a class of organic carboxylic acids containing both carboxyl (–COOH) and hydroxyl (–OH) functional groups in their molecules, are of considerable scientific and practical interest. Due to their physicochemical properties, they are capable of lowering the pH of the feed environment, creating unfavorable conditions for the growth of pathogenic and opportunistic microorganisms, and stabilizing the microbiological status of feed raw materials (Dittoe et al., 2018; Gerzilov & Hristakieva, 2025). These properties contribute to extending feed shelf life and reducing the risk of spoilage.

In addition to their technological function, certain hydroxy acids (in particular lactic, citric, and malic acids) are natural metabolites in animals and poultry and are involved in key energy processes, including the tricarboxylic acid cycle. This determines their biological compatibility and potential positive role in regulating metabolism, digestion, and intestinal microbiota. Thus, the use of hydroxy acids in feed combines the functions of a technological preservative and a biologically active additive, which can contribute to improving the physiological condition of animals and poultry (Khan et al., 2022).

Owning to the gradual restriction of the use of antibiotics as growth promoters in accordance with international regulatory requirements, particularly within European legislation, there is a need to find safe alternatives that can ensure the stability of the intestinal microbiota and maintain animal productivity (Gadde et al., 2017). Organic acids and their derivatives are considered one of the most promising approaches, as they combine antimicrobial, metabolically active, and immunomodulatory properties.

In animals and poultry, hydroxy acids can act as feed preservatives and functional additives, helping to reduce microbial load in feed, improve digestion, enhance nutrient absorption, and stabilize the intestinal environment. This is especially important under intensive farming conditions, where high growth rates are accompanied by significant stress on the digestive and immune systems (Wei et al., 2021).

An additional challenge for the industry is the increased risk of feed contamination with mycotoxins, which necessitates the introduction of effective and environmentally safe prevention strategies. In this regard, the use of hydroxy acids as natural preservatives and bioregulators represents a relevant area of research aimed at improving feed quality, ensuring the safety of livestock products, and aligning production practices with modern international animal welfare standards.

Thus, studying the mechanisms of action, effectiveness, and practical application of organic acids and their derivatives in animal and poultry nutrition is a scientifically sound and promising direction that integrates technological, biological, and veterinary-sanitary aspects of modern agricultural production.

Aim of the study. The aim of the study is to summarize current scientific data on the use of organic acids, particularly hydroxy acids, as preservatives in feed for farm animals. The study analyzes the mechanisms of their antimicrobial action, their effects on the microbiological stability of feed, and their role in regulating digestive and metabolic processes in animals. Particular attention is paid to evaluating the effects of organic acids on the gastrointestinal tract, nutrient absorption, microbiota development, and the course of key biochemical metabolic processes. A synthesis of findings from recent studies makes it possible to substantiate the feasibility of using organic acids in feed production as an effective means of improving the safety, stability, and biological value of feed products.

Results and discussion. *1. The biological role of organic acids in the regulation of metabolic processes.* Modern strategies for intensifying livestock production are based on an understanding of biochemical and microbiological processes occurring in the gastrointestinal tract. In this context, organic acids are considered important regulators of microbiota and metabolism, influencing feed quality, digestion, nutrient absorption, and animal performance.

One of the key aspects of the beneficial effects of organic acids is their involvement in the formation and regulation of the metabolic activity of the intestinal microbiota. Studies have shown that microbial fermentation of carbohydrates and amino acids in the intestine leads to the formation of short-chain fatty acids (SCFAs), particularly acetate, propionate, and butyrate, which perform important physiological functions in animals (Belzer et al., 2017). These metabolites are produced as a result of complex interactions among different groups of microorganisms involved in so-called *cross-feeding*, whereby the metabolic products of some bacteria serve as substrates for others. For example, compounds such as lactate, succinate, or propane-1,2-diol can be utilized by other microorganisms for the synthesis of propionate or butyrate (Louis & Flint, 2017).

The optimization of SCFA production and their absorption in the host depends directly on the ecophysiological characteristics of the producing bacteria and the composition of the diet. This contributes to the inhibition of pathogenic microorganisms, meets the energy demands of intestinal epithelial cells, and supports systemic metabolic homeostasis. Short-chain fatty acids not only serve as energy sources but also function as signaling molecules. They can interact with G protein-coupled receptors (GPCRs) and inhibit histone deacetylase activity, thereby contributing to the epigenetic regulation of gene expression (Koh et al., 2016; Makki et al., 2018). As a result, SCFAs regulate immune responses, lipid and carbohydrate metabolism, and support intestinal barrier integrity.

The intestinal microbiota effectively functions as a distinct metabolic organ capable of synthesizing amino acids, transforming bile acids, producing indole compounds and polyamines, and fermenting complex carbohydrates. Among the products of microbial metabolism, SCFAs are of particular importance, as they act as key mediators linking diet composition, gut microbiota, and host energy metabolism (Rauf et al., 2022; Wang et al., 2024).

2. Technological aspects of feed production and their impact on microbiological status

Technological features of feed production play an important role in ensuring the microbiological quality of feed. The effectiveness of feed preservation and utilization largely depends on the degree of ingredient grinding and the conditions of hydrothermal processing, such as pelleting or extrusion.

Reducing feed particle size increases the surface area available for interaction with digestive enzymes and may enhance digestion efficiency. However, excessively fine grinding can adversely affect the morphofunctional state of the digestive system, increasing the risk of gastric lesions in animals and poultry. In contrast, the use of coarser grinding promotes natural acidification of the stomach and the distal intestine, thereby creating a barrier against the development of pathogenic microorganisms such as *Salmonella* and pathogenic strains of *Escherichia coli* (Kiarie & Mills, 2019).

Modern hydrothermal processing technologies are aimed at feed decontamination and improving nutrient digestibility. However, high conditioning temperatures may reduce the effectiveness of heat-sensitive additives, particularly enzymes and organic acids. In the context of the withdrawal of antibiotics as growth promoters, feed production technologies are increasingly evaluated based on their ability to preserve the activity of biologically active substances and maintain optimal parameters of the morphofunctional state of the animal intestine (Ege et al., 2019).

3. Metabolic effects of organic acids and their derivatives

An analysis of scientific publications indicates that organic acids can influence not only the microbiological stability of feed but also metabolic processes in animals. Examples of such compounds include methionine hydroxy analogues (MHA), which are widely used in ruminant diets (Li et al., 2022; Zhong et al., 2024).

The use of calcium salt of MHA (MHA-Ca) and isopropyl ester of 2-hydroxy-4-(methylthio)butanoic acid (HMBi) is associated with increased rumen microbial diversity and higher concentrations of volatile fatty acids, particularly acetate and propionate. Metabolic studies indicate that these compounds can influence amino acid, carbohydrate, and lipid metabolism, including the metabolism of phenylalanine, tryptophan, tyrosine, and galactose.

Organic acids and microbial fermentation products are capable of modulating metabolic processes through interactions with specific cellular receptors. In particular, short-chain fatty acids

(SCFAs) can activate free fatty acid receptors (FFAR1–FFAR4) and hydroxycarboxylic acid receptors (HCAR1 and HCAR2), which are involved in the regulation of energy metabolism (Mielenz, 2017; Durand et al., 2024).

These mechanisms are associated with the regulation of insulin secretion, lipolysis, adipose tissue differentiation, and immune responses. In ruminants, they are of particular importance during periods of high productivity, when disturbances in energy balance may lead to the development of metabolic disorders (Alarcon et al., 2018). Fatty acids and hydroxycarboxylic acids act as important intermediates of energy metabolism and play a key role in the regulation of metabolic and immune processes underlying animal productivity.

Disturbances in energy balance, particularly during periods of high milk production or in the postpartum period, are often accompanied by metabolic shifts, increased mobilization of fat reserves, and the development of systemic inflammatory responses. Such changes may lead to the activation of mechanisms of so-called sterile inflammation, which occurs in the absence of pathogenic microorganisms but is associated with disturbances in metabolic homeostasis.

Thus, organic acids can be considered biologically active compounds capable of regulating intestinal microbiota, energy metabolism, and immune responses. This highlights their importance in modern approaches to animal nutrition and the maintenance of metabolic health in farm animals.

4. Bioactive plant compounds and their interaction with organic acids

The composition of animal diets can significantly influence the chemical composition and functional properties of animal products, particularly milk (Avila-Nava et al., 2023; Lu et al., 2025). The use of antioxidants and phenolic compounds of plant origin can improve the lipid profile of milk and enhance its antioxidant activity.

Particular attention has been paid to *p*-hydroxycinnamic acids (*p*-HCA), which are characterized by pronounced antioxidant, anti-inflammatory, and antimicrobial properties (Ma et al., 2025; Leonard et al., 2021). Their interaction with intestinal microorganisms is considered one of the mechanisms underlying their beneficial effects on animal health and productivity. In the context of developing safe and environmentally sustainable technologies, the use of such bioactive compounds is a promising approach to improving feed quality and the quality of animal-derived food products.

Experimental studies have shown that ferulic acid improves intestinal development in piglets with intrauterine growth retardation. Its application enhances the activity of antioxidant enzymes (superoxide dismutase and catalase), increases villus height, and improves intestinal enzymatic activity (Wan et al., 2022; Dong et al., 2016). As a result, improvements in feed efficiency and intestinal functional status are observed. These findings highlight the role of phenolic acids as bioactive compounds capable of modulating antioxidant mechanisms and the development of the digestive system in young animals.

5. Organic acids as an alternative to antibiotics in animal nutrition

In the context of increasing regulatory restrictions on the use of antibiotics as growth promoters in animal production, as well as growing global concern about antimicrobial resistance and residues of antimicrobial agents in animal-derived products, considerable attention has been paid to the search for alternative approaches to optimizing animal nutrition. Among the potential solutions, natural biologically active compounds, particularly organic acids and plant-derived essential oils, occupy a prominent place (Nhara et al., 2024).

Organic acids are widely used in pig production as an effective alternative to antibiotic growth promoters. Their mode of action is based on their ability to lower pH in the gastrointestinal tract, thereby creating unfavorable conditions for the growth of pathogenic microorganisms and promoting the stabilization of intestinal microbiota (Tugnoli et al., 2020; Ferronato & Prandini, 2020). In addition to their antimicrobial effects, these compounds improve digestive processes, enhance the digestibility of nutrients and minerals, stimulate the secretion of digestive enzymes, and optimize feed utilization, which positively affects animal productivity and product quality (Pearlin et al., 2020; Lone et al., 2022).

The effectiveness of these compounds largely depends on their chemical characteristics, particularly the acid dissociation constant (pKa), which influences the degree of ionization in different segments of the gastrointestinal tract. The use of blends of organic acids often provides higher biological efficacy compared to individual components due to synergistic interactions and a broader spectrum of antimicrobial activity (Nguyen et al., 2020; Rathnayake et al., 2021). As a result, growth performance, nutrient digestibility, intestinal microbiota status, and gut integrity are improved, and gas production during digestion may be reduced.

Enhancing the effectiveness of these additives is achieved through the implementation of modern technological approaches, particularly microencapsulation and the development of protected forms. These strategies contribute to the stability of active substances and their controlled release in specific segments of the intestine, thereby enhancing their biological activity and improving their efficiency in animal diets. At the same time, the response of the animal organism may depend on the type of acid, its dosage, diet composition, as well as the age and physiological status of the animals (Suiryanrayna & Ramana, 2015).

6. Application of organic acids in the nutrition of weaned piglets

Experimental studies confirm the effectiveness of the combined use of organic acids in the nutrition of weaned piglets. The combination of benzoic acid with different doses of sodium butyrate contributes to improved growth performance and modulation of the intestinal microbiota, increasing the abundance of beneficial bacteria while reducing the levels of pathogenic microorganisms (Wei et al., 2021; Choi & Kim, 2024).

The obtained results indicate that the combined application of organic acids may have a synergistic effect, contributing to improved growth and the establishment of a more stable intestinal microbiota in piglets.

7. Use of organic acids in poultry farming

Following the ban on the use of antibiotic growth promoters in the European Union, interest in alternative feed additives in poultry production has increased significantly (Rahman et al., 2022; Gadde et al., 2017; Kalia et al., 2022). Organic acids and their salts are characterized by antimicrobial, metabolic, and immunomodulatory properties. Their use contributes to the regulation of pH in the gastrointestinal tract, suppression of pathogenic microflora, maintenance of eubiosis, and improvement of nutrient digestibility, which positively affects growth performance and the overall physiological status of poultry (Gerzilov & Hristakieva, 2025; Zhu et al., 2021; Dai et al., 2021).

Studies indicate that the inclusion of lactic, propionic, and butyric acids in broiler diets improves performance indicators, enhances antioxidant status, and stabilizes metabolic processes (Samy & Elsherif, 2025; Zhang et al., 2023).

In addition, compound acidifiers can increase the activity of antioxidant enzymes, modify the blood lipid profile, and regulate the expression of genes involved in hepatic lipid metabolism (Cai et al., 2025).

A promising approach is the combination of organic acids with plant-derived bioactive compounds, particularly tannins or essential oils, which contributes to improved poultry growth, enhanced morphofunctional status of intestinal structures, and improved immune status (Khorasgani et al., 2025; Xu et al., 2023). It has been established that the combination of hydrolyzed tannin and organic acids (1 g/kg HT + 2 g/kg OA) improves average daily weight gain, reduces feed conversion ratio, and decreases abdominal fat deposition without negatively affecting intestinal microbiota. The application of this mixture is associated with reduced pH in the stomach and ileum, suppression of *Escherichia coli*, increased abundance of *Lactobacillus*, and improved intestinal morphology (villus height, villus-to-crypt ratio, absorptive surface area). Additionally, positive changes in the structure of immune organs have been observed. These findings confirm the synergistic effect of combining organic acids with phenolic compounds on growth performance, immune status, and intestinal function in broilers (Dittoe et al., 2018; Khan & Iqbal, 2016).

Modern broiler strains are characterized by rapid growth and reach market weight at approximately five weeks of age, which necessitates optimization of feeding strategies and stable functioning of the digestive system (Khan et al., 2022). Organic acids, as weak acids with partial dissociation, have long been used as safe preservatives and exhibit antibacterial, immunostimulatory, and growth-promoting properties.

Experimental evidence shows that supplementation with mixtures of organic acids (3000–6000 mg/kg), including products such as Fysal MP, improves immunological parameters (IgA, IL-10) and antioxidant status (SOD, CAT), reduces pH in the duodenum, enhances digestive enzyme activity, and increases the expression of tight junction proteins, thereby strengthening intestinal barrier function (Ma et al., 2021; Wang et al., 2022). A reduction in *Escherichia coli* counts and improved growth performance at lower inclusion levels have also been reported, indicating economic feasibility.

Recent studies confirm the effectiveness of organic acid blends, including products such as Acidapure, as alternatives to antibiotic growth promoters (Waghmare et al., 2025). Their use during a 42-day broiler production cycle contributes to increased body weight, improved feed conversion, optimized intestinal morphology, and reduced levels of coliform bacteria. Additionally, a positive effect on blood lipid profile has been observed, confirming the complex metabolic action of organic acids.

Studies have also demonstrated the effectiveness of apple cider vinegar and essential oils administered via drinking water in broilers. Such additives improve growth performance, reduce cholesterol levels, and enhance antioxidant status (Ashayerizadeh et al., 2025; Selim et al., 2024).

Similar effects have been observed with combinations of organic acids and essential oils, which stimulate digestive enzyme activity, improve intestinal morphology, and increase the level of secretory immunoglobulin A in the intestinal mucosa (Yang et al., 2018; Adewole et al., 2021).

Conclusions.

1. The available scientific evidence demonstrates that organic acids, in particular hydroxy acids, play an important role in ensuring the microbiological stability of feed and maintaining the metabolic homeostasis of animals. Their use contributes to lowering the pH of the feed environment, suppressing the development of pathogenic microorganisms, and increasing the sanitary safety of feed products.

2. The biological effect of organic acids is associated with their influence on the intestinal microbiota and microbial fermentation processes, accompanied by the formation of short-chain fatty acids. These metabolites perform energy and signaling functions, participate in the regulation of the immune response, intestinal barrier function, and lipid and carbohydrate metabolism.

3. The effectiveness of using organic acids in animal feed largely depends on the technological parameters of feed production, in particular the degree of grinding of ingredients, hydrothermal treatment modes, and the stability of biologically active additives. Modern technologies, including microencapsulation and the use of complex acidifiers, make it possible to increase their biological availability and effectiveness.

4. Studies show that organic acids and their derivatives can influence key metabolic processes, including the metabolism of amino acids, carbohydrates, and lipids, as well as regulate the functional state of the intestinal microbiota and immune system. A promising direction is their combined use with bioactive plant compounds (phenolic acids, tannins, essential oils), which can enhance antioxidant, antimicrobial, and metabolic effects.

5. Practical results of research in pig and poultry farming confirm that the use of organic acids and their mixtures contributes to improved growth performance, increased feed efficiency, stabilization of intestinal microbiota, and strengthening of the immune status of animals. Owning to restrictions on the use of antibiotics as growth promoters, organic acids are considered a promising and safe alternative for increasing productivity and ensuring animal health.

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