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Modern biotechnological solutions in the prevention and control of coccidiosis in piglets on pig farms in Southern Ukraine

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Abstract. The aim was to theoretically substantiate and develop practical recommendations for a comprehensive biotechnological approach to disease prevention, specially adapted to the regional conditions of southern Ukraine. The materials were processed using methods of theoretical and methodological analysis, systematic and comparative analysis, analytical and synthetic generalisation, analogy and methodological design of practical recommendations. As a result of the study, the epizootic process of coccidiosis in piglets in farms in southern Ukraine was interpreted as being sustained by a combination of the environmental reservoir of Cystoisospora suis oocysts and technologically induced repeated contamination of bedding and production surfaces. The key factors determining the invasive pressure in the holding sections are the interaction of the microclimate of the premises with the modes of moistening/drying of substrates within the technological cycle, in particular during prolonged periods of high temperatures in the warm season and the presence of local areas of stable moisture. On this basis, prevention is described as managing the links "source of invasion – environment – susceptible contingent" with priority given to measures that reduce the persistence of invasive material between batches and limit the re-seeding of the environment. The limits of applicability of monochemical schemes in systems where the environmental component of transmission is preserved are justified, and the risks relevant to the microbiome, biosafety and environmental consequences of the prolonged presence of anticoccidial agents are outlined. A criteria-based intervention assessment scheme has been operationalised through a coordinated set of indicators reflecting parasitological, clinical and production outcomes. An integrated protocol has been proposed that combines sanitary and hygienic contamination control, biotechnological interventions, and standardised monitoring based on the "before/after" principle. The practical significance lies in the possibility of implementing a unified algorithm for prevention and control in farms in southern Ukraine with reproducible performance evaluation and comparability of effects between sections and production cycles

Keywords: epizootic pressure; vaccination; mucosal immunity; probiotics; antibiotic resistance

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INTRODUCTION

Coccidiosis in piglets associated with *Cystoisospora suis* is a problem of manageability in the early stages of rearing in industrial pig farming, since even short-term enteropathies quickly convert into measurable losses in productivity (weight gain, feed conversion), an increase in culling rates and higher costs for treatment and preventive measures. For the southern regions of Ukraine, the relevance is exacerbated by a combination of high temperatures during the warm season and microclimatic conditions in the housing sections (local humidity of bedding/surfaces, uneven drying between technological cycles), which contributes to the preservation of the environmental reservoir of oocysts and repeated contamination. Under such conditions, drug prophylaxis may demonstrate limited stability of effect if technological transmission routes are not controlled. In addition, the importance of biosafety and environmental justification of protocols (impact on intestinal ecology, selective resistance pressure, consequences of waste management) is increasing, which determines the need for integrated solutions with standardised monitoring of parasitological, clinical and production indicators.

In production conditions, early chemoprophylaxis of coccidiosis in piglets was considered as one of the approaches to reducing the intensity of oocyst excretion and the frequency of diarrhoeal syndromes in the suckling period. In a field study by V. Skampardonis *et al*. (2010), the effect of toltrazuril in suckling piglets with natural infection *with Isospora suis* was analysed using productive and epizootological relevant indicators, which allowed linking pharmacological intervention with the course of invasion at the group and farm levels. Clarifying the role of the environmental reservoir of invasion required tools capable of reflecting not only faecal oocyst excretion, but also the level of contamination of technological surfaces and critical areas of the machine. H. Loesing *et al*. (2025) evaluated the sponge sampling approach in combination with real-time PCR for the detection of *Cystoisospora suis* in environmental and faecal samples on piglet farms, which expanded the methodological basis for monitoring by including “environmental” samples in the epizootic surveillance system. These results were considered as a methodological basis for constructing a diagnostic contour in which the assessment of prevention effectiveness included indicators of environmental contamination along with coprological control data.

In a study by H.G. Araújo *et al*. (2020) described the diversity of enteric coccidia in pigs in the semi-arid region of Northeast Brazil, confirming the presence of several coccidian agents in the herd and emphasising the usefulness of species verification in the analysis of protozoa. In the context of controlling coccidiosis in piglets, these data were interpreted as an argument in favour of differentiated diagnosis, where the detection of oocysts in faeces was considered taking into account the potential polyetiological nature of the coccidiosis background. G. Deak *et al*. (2024) in a field study on intensive farms in south-eastern Spain simultaneously evaluated the effectiveness of prophylactic toltrazuril and the diagnostic detectability *of Cystoisospora suis* in 1-3-week-old piglets using flotation-concentration approaches for oocyst detection. It was shown that oocysts were detected in all farms, and the risk/frequency of detection was associated with age, the presence of diarrhoea and certain housing parameters (in particular, the type of pen flooring), which emphasised the importance of environmental reservoirs and management alongside pharmacological prophylaxis.

A. Jankowska-Mąkosa *et al*. (2023) analysed the level of parasitic infection in pigs as an indicator of production sustainability, linking parasitic load to farm productivity and resource costs. The study demonstrates the practical feasibility of including parasitic disease indicators in the “health-productivity-resource efficiency” assessment system, which allows for the justification of preventive programmes as an element of sustainable pig farming management. A. Shrestha *et al*. (2015) presented *Cystoisospora suis* as a model of mammalian cystoisosporosis, systematising the key links in pathogenesis and age windows of greatest susceptibility in suckling piglets. The publication summarises that early damage to enterocytes and disruption of the mucosal barrier function create the conditions for clinical diarrhoea and secondary complications, and therefore control must take into account not only the pharmacological component, but also environmental factors and husbandry techniques. E. Straberg & A. Daugschies (2007) experimentally evaluated the effectiveness of a cresol-containing agent for inactivating oocysts and reducing infectious pressure under production conditions, demonstrating the suitability of disinfection as a means of breaking the transmission cycle. The results justified the inclusion of targeted disinfection protocols in control programmes as a tool to reduce contamination of critical areas of the machine and bedding. As noted by O. Bohach *et al*. (2023) in their work, cases of mixed infections, such as isosporosis with cryptosporidiosis, require attention. Such associations of pathogens are characterised by a more severe clinical course and require the development of special comprehensive treatment and prevention protocols. The authors emphasised the importance of accurate diagnosis of each component of the infestation for the prescription of effective therapy, as different protozoa may have different sensitivities to drugs.

The scientific reviews, including the work of J.P. Dubey & M. Santín (2025), systematise fundamental knowledge about coccidiosis. The authors stated that *Cystoisospora suis* remains the main causative agent of coccidiosis in piglets worldwide, and its life cycle and pathogenesis are well studied. In their review, the authors also discussed current trends in diagnosis, prevention and control, providing a comprehensive basis for further research and practical solutions. An understanding of the geographical distribution of pathogens is necessary for the development of regionally adapted control strategies. The study by H. Han *et al*. (2024) focuses on this aspect: the authors conducted a scoping review of coccidia species parasitising pigs of the genus *Sus* and analysed their distribution worldwide. This work emphasises that the epizootiological picture may vary from region to region, which is critical for planning effective national and local disease control programmes.

Despite the large number of publications, most studies focus on specific aspects of coccidiosis in pigs, such as the prevalence of the pathogen or the identification of risk factors, without simultaneously analysing biological, technological and regional climatic factors. Some of the studies are regionally specific or based on cross-sectional survey data, which limits the possibility of comparing results between different husbandry systems. In addition, there is a lack of systematic data in the literature on comprehensive preventive approaches combining biotechnological solutions and elements of production management, as well as a lack of studies aimed at analysing the specifics of coccidiosis control in pig farms in southern Ukraine. The aim of the work was to conduct a theoretical analysis of modern biotechnological approaches to the prevention and control of coccidiosis in piglets and to summarise scientific and production data, taking into account the climatic characteristics of southern Ukraine. To achieve this goal, three main tasks were identified: to analyse the impact of specific climatic conditions of the region on the epizootology of coccidiosis; to assess the limitations of traditional methods of chemical prevention; to systematise modern biotechnological solutions (vaccination, immunostimulation, probiotics and prebiotics) and justify their adaptation to local production realities.

MATERIALS AND METHODS

The methodological basis of the study was formed within the framework of a theoretical and empirical approach and was based on a combination of theoretical analysis of scientific sources with the generalisation of quantitative and qualitative data from previous experimental and field studies and the application of a set of complementary methods: theoretical and methodological analysis, system analysis, comparative analysis, analytical and synthetic generalisation, the analogy method, and the methodical design of practical recommendations. This approach was applied taking into account the climatic and production characteristics of pig farms in southern Ukraine, which are characterised by elevated temperatures and conditions that affect the survival and circulation of *Cystoisospora suis* oocysts. The object of the study was the process of prevention and control of coccidiosis in piglets in industrial pig farms. The subject of the study was biotechnological approaches to the control of coccidiosis, in particular the use of vaccines, probiotics and prebiotics, as well as the features of their integration into the system of preventive measures, taking into account regional climatic factors. Data collection and selection for theoretical and empirical generalisation was carried out based on publications from 2019-2025, taking into account their relevance to the topic of *Cystoisospora suis* control in pig farming and regional climatic conditions similar to those in southern Ukraine. The analysis included sources containing measurable parasitological, clinical and/or production outputs (oocyst excretion/infestation, frequency of diarrhoea/enteritis, weight gain, feed conversion, mucosal morphometry, resistance indicators), as well as describing the methods of diagnosis, prevention and management used in farms or controlled experiments. Additional criteria were full-text availability, clarity of design and the ability to compare results on a "control/intervention" or "before/after" basis within a specific study. The study employed theoretical and methodological analysis to substantiate the impact of climatic conditions in southern Ukraine on the life cycle *of Cystoisospora suis,* as well as to analyse the immune and microbiome mechanisms involved in the formation of antiparasitic protection in pigs. Within this approach, current ideas about the pathogenesis of coccidiosis, the interaction of the pathogen with the intestinal microbiome and the immune system of animals were analysed. This method was applied using regional data from the Odesa region and generalisations about risk factors and the spread of invasions (Bohach *et al*., 2024), as well as observational data for European farms with similar climatic conditions and different levels of biosecurity/hygiene (Nunes *et al*., 2023).

System analysis was used to integrate data on regional climatic conditions, epizootic pressure, chemoprophylaxis limitations, and the potential of biotechnological solutions into a single cause-and-effect logic for coccidiosis control. Within this approach, production and microclimatic factors were operationalised as controllable determinants of invasive pressure, in particular the moistening/drying regime of substrates, the presence of persistent wet areas (near drinking troughs, in washing areas and areas where liquid fractions accumulate), ventilation parameters and stocking density, which determined the rate of surface drying and the duration of preservation of invasive material. The effectiveness of preventive strategies was assessed using multiple criteria: taking into account productive and clinical indicators, changes in the intestinal ecosystem (microbiome/signs of dysbiosis and barrier indicators), biosafety risks (formation/spread of antimicrobial resistance) and the environmental acceptability of use (persistence of active substances and potential environmental contamination). Within this method, sources describing the seasonal/microclimatic interaction between host and pathogen and the influence of season, age and management practices on parasitic diseases in pigs (Fay *et al.*, 2025; Senanayake *et al.*, 2025), combined with regional materials on the structure of protozoan invasions and farm typology (Bogach & Avhitova, 2019).

Comparative analysis was used according to clearly defined criteria of efficacy and safety, namely: average daily gains, feed conversion, frequency of diarrhoea syndrome in risk groups, morphometric indicators of the mucosa (height of villi in the small intestine) and indicators of non-specific resistance (in particular, the phagocytic index). The effectiveness was assessed using the "before/after" principle by comparing the specified indicators in comparable groups/conditions. This method was implemented based on data on the effectiveness of protozoal drugs in cases of associative invasions in regional conditions (Bogach & Avhitova, 2019). For the biosafety component, data on the risks of resistance selection when using ionophores (Simjee & Tice, 2023) ecological pathways and consequences of ionophore persistence in livestock systems (Alam *et al.*, 2025), and pharmacological characteristics of the drug group as a basis for biosafety/environmental criteria (Dowling & Baptiste, 2024).

Analytical and synthetic generalisation was used to convert data from selected publications into a comparable array of indicators and subsequently form generalised conclusions. At the analytical stage, the following were extracted from each source comparison design (control/intervention or "before/after"), type of intervention and measured outcomes (oocyst excretion/infestation, diarrhoea, weight gain, conversion, mucosal morphometry, resistance indicators) were extracted from each source, together with the direction and magnitude of the effect. At the synthetic stage, these data were coded according to the "target → indicator → outcome" scheme and summarised (formation of effect intervals and a minimum set of monitoring indicators), without conclusions that are not confirmed by the actual indicators presented. Analytical and synthetic generalisation was carried out on the basis of sources describing the acquired intestinal immune response to coccidiosis and the principles of vaccine prophylaxis, antigenic/immunogenic properties of gametogenic antigens of coccidia as potential vaccine targets, and features of antiparasitic immunity in pigs (Baker *et al.*, 1994; Lillehoj & Lillehoj, 2000; Wang *et al.*, 2025). Additionally, approaches to mucosal vaccines for parasitic infections and generalisations regarding coccidiosis in pigs relevant to the interpretation of age susceptibility and immune responses were taken into account (Joachim & Shrestha, 2019; Kato, 2020). Empirical data on combined regimens (vaccine + probiotic complex) were used to summarise typical indicators of the effect on productivity and microbiota under controlled infection (Cai *et al.*, 2023). To clarify the mechanisms of mucosal protection and current alternatives to antibiotics, reviews on advances in the study of immunity in coccidiosis and antibiotic replacement strategies, as well as data on the mucosal immune response in gastrointestinal helminthiasis as a comparable model of barrier resistance, were used (Lee *et al.*, 2022; Palkumbura *et al.*, 2024). For the block of immunomodulatory approaches and prevention practices, additional sources were considered that highlighted the role of vaccination in controlling infections/zoonoses in pigs and data on changes in immunological parameters when using dietary supplements in pig feed (Klikin *et al.*, 2024; Arutkumaran *et al.*, 2025). Microbiome-oriented interventions (probiotics/prebiotics) were also analysed with quantitative indicators of productivity, morphofunctional state of the mucosa and clinical indicators (Agazzi *et al.*, 2020; Begma, 2023; Kolechko *et al.*, 2023).

The analogy method was used to adapt individual approaches tested in related livestock sectors, with subsequent adjustments in line with the biological and production characteristics of pig farming. As part of this method, the principles of controlling the transmission of *Cystoisospora suis* through the prophylactic use of toltrazuril were transferred to the logic of integrated prevention programmes combining management and biological interventions (Lara *et al.*, 2022). In addition, technologically proven vaccine strategies against coccidia in poultry farming and framework approaches to replacing antibiotics in pig/poultry farming were used as reference examples (Albanese *et al.*, 2018; Thong & Duc, 2022). The correctness of the transfer to pig farms was clarified taking into account clinical and practical provisions regarding restrictions on the routine use of antibiotics and strategic arguments in favour of the development of veterinary vaccines as a long-term tool for controlling parasitic diseases (Sander *et al.*, 2020; Memon *et al.*, 2022; Burrough *et al.*, 2025). At the final stage, recommendations were developed aimed at forming a theoretically sound algorithm for the comprehensive use of biotechnological agents in the coccidiosis prevention system, taking into account regional conditions.

RESULTS

The influence of climatic conditions in Southern Ukraine on the formation of the epizootic situation of coccidiosis

The climatic conditions of southern Ukraine determine the specifics of the epizootic process of cystoisosporosis in piglets, primarily due to the dependence of the extra-organism stages of the pathogen on temperature and humidity. At elevated temperatures combined with sufficient humidity, the transition of oocysts to the invasive form (sporogony) is accelerated, and in the presence of moist substrates, the period of their viability is prolonged. Thus, for farms in the region, it is not so much the average climatic indicator that is important, but how the climate is realised within the premises – through the regime of moistening and drying of litter, surfaces and equipment between technological cycles. In production conditions, this manifests itself in the fact that even under the same external weather conditions, the invasive pressure can vary depending on ventilation, stocking density, local water sources (drinking troughs, washing, leaks), accumulation of liquid manure fractions and the frequency of sanitary treatment of sections.

The clinical and pathogenetic manifestations of coccidiosis reinforce this dependence, since damage to the small intestine in early-age piglets is accompanied by a disruption of the barrier function, changes in the architecture of the mucous membrane, and the development of diarrhoea syndrome. Diarrhoea in this system has not only clinical significance, but also epizootic significance: increased moisture content of faecal masses and increased contamination volume contribute to the formation of local wet micro-foci in the pen and increase the likelihood of invasive material remaining in substrates that do not dry out completely. Thus, maintaining moisture in the section creates conditions under which rapidly maturing oocysts are preserved long enough to ensure repeated contamination of surfaces and transmission of the invasion between groups or between successive batches of piglets. For the southern regions of Ukraine (Odesa, Kherson, Mykolaiv, Zaporizhzhia), the warm season is characterised by temperature conditions that shorten the maturation of oocysts, and in the presence of moisture in the substrates, the viability of the invasive material is maintained within a time frame sufficient to maintain circulation within the technological cycle. In practical terms, this means that the key controllable factor is not the hot season itself, but the ability of the farm to ensure complete drying of surfaces and bedding between cycles of detention and to minimise areas of chronic moisture. It is these points (wet areas of the floor, areas under drinkers, places where liquid fractions accumulate) that determine the persistence of contamination and the re-seeding of the section with invasive material.

Empirical observations for the Odesa region are consistent with this logic: the infection rate of suckling piglets *with Cystoisospora suis* at 40.3% reflects the preservation of invasive material in the environment and the presence of conditions for its maintenance in critical areas of the section (Bohach *et al.*, 2024). At the same time, data from European farms show that under similar climatic conditions, the spread of the invasion varies significantly depending on the level of biosecurity and hygiene, i.e., the climate acts as a backdrop against which management decisions are made (Nunes *et al.*, 2023). In this context, technological variables – the frequency and quality of sanitation, the organisation of animal flows, adherence to the principle of "everything is empty – all occupied" principle, and humidity control in the section – become factors that either break the chain of transmission or, conversely, stabilise repeated contamination (Fay *et al.*, 2025; Senanayake *et al.*, 2025). An additional argument in favour of the decisive role of hydrothermal conditions is that within the Northern Black Sea region, shifts in the structure of protozoan invasions are recorded depending on the humidity of the area. Under conditions of a summer decrease in the hydrothermal coefficient (0.3-0.5), the incidence of *Isospora suis* in suckling piglets was 27.6% and *Cryptosporidium spp.* 6.9%, while in more humid areas (1-1.4), the infestation rate of *Cryptosporidium spp*. was 18.5% higher (Bogach & Avhitova, 2019). These ratios indicate that the water regime of the environment (both at the level of the microclimate of the premises and at the level of local natural and climatic differences) can influence not only the intensity of protozoan load, but also the profile of dominant agents, which should be taken into account when selecting prevention priorities.

The dependence of protozoan intensity on the type of farm is also indicative: the overall infestation rate in large farms (>100 sows) was 41.5%, in medium-sized farms (25-100) – 66.1%, in small farms (<25) – 77.9%, and the proportion of mixed infections in small farms reached 36.9%, with mono-infections predominating in large farms (74.9%). These data support the conclusion that, given the climatic conditions of the region, organisational and hygienic practices and environmental humidity management remain decisive factors in determining the frequency of re-contamination and the conditions for the transmission of invasive material. As a result, the combination of warm season temperature and humidity conditions and the maintenance of moisture in the substrates leads to the formation of constant *Cystoisospora suis* infestation pressure in farms in southern Ukraine, which persists due to repeated contamination of sections between technological cycles.

Disadvantages of traditional chemoprophylactic approaches in regional conditions

In industrial pig farming, chemoprophylaxis of coccidiosis is often perceived as a quick tool for reducing clinical manifestations in risk groups. however, in farms in southern Ukraine, its effectiveness and acceptability are determined not only by antiparasitic activity, but also by systemic consequences that manifest themselves at the level of intestinal ecology, biosafety and environmental safety of production. In a region where temperature loads increase during the warm season and stable microclimate control in sections becomes more difficult, any preventive intervention actually works in conditions of increased sensitivity of piglets to enteropathies and dysbiotic shifts. That is why traditional schemes, which boil down to the routine use of chemoprophylactic agents without reference to stress periods, the structure of invasions and sanitary and hygienic restrictions of a particular farm, have a predictably narrow window of effectiveness and can create secondary problems that negate the expected preventive result.

One of the key reasons for limited effectiveness in southern Ukraine is the overlap of pharmacological intervention with heat stress factors. High temperatures in summer and transitional periods with significant daily temperature fluctuations are usually accompanied by changes in feed and water consumption, fluctuations in intestinal motility, increased microbiota lability, and changes in the barrier function of the mucosa. Under such conditions, reducing the invasive load with medication alone does not guarantee clinical stabilisation, since diarrhoea syndrome in piglets in real production conditions is a multifactorial phenomenon and is maintained by a chain of stress → barrier disruption → dysbiosis → inflammation, which can persist even with partial control of the protozoan component. As a result, prophylaxis formally directed against coccidia during the warm season should often be evaluated not only by the fact of its use, but also by whether it is possible to prevent the destabilisation of the intestinal ecosystem and secondary complications that increase the severity of enteropathies.

The second systemic aspect is the effect of chemoprophylaxis, in particular ionophore coccidiostats, on the intestinal microbiome and, accordingly, on microbiome-dependent resistance mechanisms. In prophylactic (subtherapeutic) regimens, such agents can shift the composition of the microbiota, which is critical in the context of early age, since during this period the microbiome is not yet stabilised and easily transitions to a dysbiotic state under the influence of stressors, changes in feeding and technological manipulations. The practical consequence is that even with a decrease in the protozoan component, colonisation resistance may deteriorate, the production of metabolites that support the epithelial barrier may change, and the susceptibility to diarrhoeal syndromes or their prolongation may increase. In southern farms, these risks are further exacerbated by the fact that heat stress and microclimatic factors often increase the frequency of wet areas in sections, which maintains the background pressure of enteropathogens and increases sensitivity to any microbiome shifts. In other words, chemoprophylaxis can create a paradoxical situation here: antiparasitic intervention is carried out, but the functional prerequisites for diarrhoea are not eliminated and are sometimes even exacerbated by undesirable effects on the microbiota.

The third set of limitations is related to biosafety and antimicrobial resistance. Sources warn that the use of ionophores creates selective pressure on enterococcus populations and may be associated with mobile genetic elements capable of transferring resistance determinants between bacterial species (Simjee & Tice, 2023). For farms, this means that a preventive strategy that does not take into account the biosafety cost potentially contributes to the formation of a reservoir of resistant strains in the intestinal ecosystem of animals and in housing substrates. In the regional conditions of southern Ukraine, this risk has an additional practical dimension: during the warm season, increased humidity in certain areas, intensive washing cycles, manure removal and contact with technological surfaces increase the likelihood of microorganisms circulating between sections and through contaminated objects. In this logic, antimicrobial resistance ceases to be a distant problem and becomes a parameter that must be taken into account when choosing prevention as an element of risk management in the production system.

The fourth aspect is the environmental component, which is increasingly being considered as part of the requirements for the safety of animal husbandry technologies. According to sources, certain coccidiostats can persist in the environment after being excreted, enter water bodies and have toxic effects on aquatic organisms even at low concentrations, while traditional treatment systems do not always ensure complete removal of such substances (Alam *et al.*, 2025). For southern Ukraine, where the practice of applying organic waste as fertiliser is widespread, this means an increased likelihood of chronic low-dose exposure in soil and water systems and a potential impact on microbial communities in the environment, the ecological trail of chemoprophylaxis should be considered not as a secondary ethical argument, but as a real component of limiting its routine use in the region.

The practical disadvantage of traditional schemes in southern farms is that they often do not take into account the structure of protozoan associations and the pattern of infestation in a particular farm. Empirical data from monitoring mixed infestations have shown that effectiveness can vary significantly depending on the pathogen: for "Brovitacocid", 66.7% extensive effectiveness was reported for balantidiasis and 88.9% for cryptosporidiosis, with simultaneously high indicators for other protozoa, while for "Amprolev-plus", 100% effectiveness was reported for the protozoa studied. In regional conditions, such differences have direct practical significance: if a farm is characterised by a stable association of protozoan agents, monodirectional prophylaxis for one typical pathogen naturally leaves room for the preservation of diarrhoeal syndromes and repeated contamination pressure, especially under conditions of heat stress and microclimate fluctuations. That is why sources describing the pharmacological characteristics of drug groups and approaches to their use emphasise the need for the rational, time-limited use of chemoprophylactic agents and the correct choice of regimen depending on farm conditions (Dowling & Baptiste, 2024). Therefore, for southern Ukraine, it is crucial that traditional chemoprophylaxis cannot be considered a self-sufficient universal strategy: its microbiome consequences, biosafety risks, environmental constraints, and variability in effectiveness against associative invasions become significant precisely in conditions of heat stress, when the stability of intestinal resistance is most vulnerable, and preventive solutions require maximum alignment with production realities and controlled indicators.

Immunological mechanisms of adapted biotechnological control of coccidiosis

Biotechnological approaches to coccidiosis control are considered through two complementary levels: specific (antigen-dependent) immunity and non-specific resistance (innate effector mechanisms and mucosal barrier) (Lillehoj & Lillehoj, 2000). The specific level is most often operationalised by markers of intestinal immunity and morphofunctional characteristics of the mucosa, while the applied significance is assessed by functional outputs, primarily by the dynamics of oocyst excretion and/or clinical manifestations of enteropathy (Baker *et al.*, 1994; Wang *et al.*, 2025). At the level of evidence, it is not the isolated increase in a single indicator (e.g., IgA or cytokines) that is decisive, but the consistency of the chain immune indicator → parasitological/clinical outcome, i.e., the correlation of changes in markers with changes in oocyst excretion and the severity of diarrhoea.

Vaccine strategies for coccidiosis in related animal systems are described as approaches aimed at developing local (intestinal) immunity and reducing the manifestations of invasion through immunological control of mucosal damage (Joachim & Shrestha, 2019; Kato, 2020). The role of secretory IgA, gut-associated lymphoid tissue and cytokine profile as mechanistic elements of the response is also emphasised, however, the applied significance for the control of coccidiosis is confirmed precisely by functional indicators (oocyst excretion/clinical manifestations/morphological markers of damage). The statement about "reproduction control" is correct only when it is linked to a measurable outcome, i.e., a reduction in oocyst excretion or a decrease in the severity of enteropathy under conditions of controlled infection or production observation (Cai *et al.*, 2023).

Non-specific resistance in the context of biotechnological control of coccidiosis is considered a resource for supporting barrier and effector mechanisms during periods of physiological and technological vulnerability (early age, weaning, heat stress) when the risk of enteropathy and microbiota imbalance increases. Immunostimulatory agents (β-glucans, nucleotides, and other agents with an immunotraining effect) are modifiers of phagocytosis and cytokine responses; accordingly, the phagocytic index and cytokine response indicators in sources are the most direct indicators of this level, while the frequency of diarrhoea is used as a clinically oriented indicator of the total effect at the intestinal level. According to this logic, immunostimulation is not a substitute for specific prophylaxis, but rather a tool whose effect should be correctly assessed through changes in indicators of non-specific resistance and clinical manifestations, rather than through assumptions about a direct impact on parasitological outcomes without relevant data.

Data on combined approaches (combining immunoprophylaxis with microbiome-oriented interventions) are heterogeneous in design and animal species, so such associations are presented as potential and limited by the scope of the relevant sources. Non-specific resistance in this context is interpreted as a resource for supporting barrier and effector mechanisms during periods of physiological and technological vulnerability. Immunostimulatory agents are described as modifiers of phagocytosis and cytokine responses, with the phagocytic index and cytokine response markers being the most direct indicators, while the frequency of diarrhoea is used as a clinically relevant summary indicator. At the same time, immunostimulation is more often presented as a component of combined programmes, and that is why its effect should be correctly assessed through changes in indicators of non-specific resistance and clinical dynamics, rather than through assumptions about direct parasitological mechanisms without appropriate measurements. The generalisation is a comparison of mechanistic indicators and functional outcomes, and the formulation of cause-and-effect mechanisms is only acceptable within designs where the relevant baseline indicators (oocyst excretion/clinical signs/productivity) are available (Table 1).

Table 1. *Generalisation of the immunological effects of vaccination and immunostimulants in the adapted coccidiosis control system*

Component of biotechnological control	Level of immunity	Main immune targets/ mechanisms (summarised)	Indicators used in sources	Type of data on which the summary was based
Vaccination (live attenuated/ antigenic approaches; principles described for coccidiosis)	Specific (mainly mucosal)	Induction of local intestinal immunity; involvement of humoral and cellular links; participation of intestinal lymphoid tissue	Secretory IgA; cell populations in the mucosa; cytokine markers; dynamics of oocyst excretion	Mechanistic and applied data on coccidiosis; transferability of principles to other species, taking into account the biology of mucosal immunity
Immunostimulants (β-glucans, nucleotides, other immunotraining agents)	Non-specific (innate; maintenance of the mucosal barrier)	Activation of innate immune receptor systems; modulation of phagocytosis and cytokine responses; support of effector mechanisms during periods of stress	Phagocytic index; markers of cytokine response; indicators of non-specific resistance; frequency of diarrhoeal syndromes as a clinical indicator	Mechanistic and experimental data on immunostimulation; interpretation for pig farming, taking into account stress factors
Combined protocols (vaccination + immunostimulation/ microbiome-oriented interventions)	Specific + non-specific	Simultaneous influence on the formation of antigen-specific response and increased readiness of effector mechanisms; potential synchronisation of immune and microbiome factors	Oocyst excretion; clinical signs of enteritis; resistance/ productivity indicators (depending on study design)	Data from related/ model studies of combined interventions used for mechanistic interpretation

Source: *compiled by the authors based on D. Baker et al. (1994), H. Lillehoj & E. Lillehoj (2000), A. Joachim & A. Shrestha (2019), H. Kato (2020), F. Wang et al. (2025)*

Table 1 correlates the levels of immune response and the type of indicators: mechanistic markers (secretory IgA, mucosal cell populations, cytokine profiles, phagocytic index) show the direction of immune modulation, while applied significance is confirmed only by functional outputs (primarily oocyst excretion dynamics, frequency of clinical manifestations of enteritis/diarrhoea and, if available, productive metrics). This division sets limits: statements about a potential reduction in the risk of transmission or “epizootic load” are linked to changes in oocyst excretion as a parasitological outcome, while changes in IgA/cytokines/phagocytosis reflect the involvement of the corresponding links of immunity without direct automatic transfer to the level of field efficacy. For combined protocols, the simultaneous presence of indicators of different nature (oocyst excretion, clinical manifestations, resistance/productivity) is recorded, but the statement about the synchronisation of immune and microbiome factors remains a mechanistic interpretation of related data.

Microbiome-oriented prevention strategies and their impact on piglet health

Within the framework of systems analysis, the intestinal microbiome was considered as a functional level through which the barrier properties of the epithelium and the immune effects of the mucous membrane were realised. Accordingly, probiotics and prebiotics were interpreted as interventions that could alter the microbial environment of the intestine (colonisation resistance, metabolite production, local pH changes, synthesis of antimicrobial peptides) and associated with changes in the frequency of diarrhoeal syndromes and productivity indicators in risk groups. Microbiome-oriented interventions were operationalised through a set of control indicators that simultaneously reflected barrier function, clinical manifestation and production effect. Accordingly, the effectiveness assessment was structured as a "before/after" comparison based on morphometric markers of the mucosa (villus height), frequency of diarrhoeal syndromes, and productivity metrics (average daily gain, feed conversion), which allowed the impact of microbiome correction to be interpreted not only mechanistically but also practically.

The logic of "before/after" the implementation of microbiome-oriented strategies was formalised by comparing conditions described in the sources as typical for technologically vulnerable periods (weaning, diet change, stress loads). In the "before" state, attention was focused on the combination of two processes: an increase in the frequency of diarrhoeal syndromes in risk groups and changes in the morphofunctional indicators of the mucous membrane, which were used as proxy indicators of barrier function. In particular, for prebiotics (MOS/FOS), morphometric data were considered as one of the operational indicators of the condition of the mucosa: the addition of MOS to weaned piglets was associated with an increase in villus height in the small intestine from 450 ± 35 μm to 520 ± 40 μm (a change of +15.6%, $p < 0.05$) (Agazzi *et al.*, 2020). This result was interpreted as a change in a parameter reflecting the absorption surface and the condition of the epithelial barrier.

In the "after" state of probiotic and/or prebiotic administration, the generalisation was based on quantitative indicators of productivity and feeding efficiency and on data on the frequency of diarrhoeal syndromes in risk groups. For *Bacillus subtilis*-based probiotics in the feeding of fattening pigs, data were reported on a 12.3% increase in average daily gains in the experimental group compared to the control (Begma, 2023). Other studies reported an increase of 8-10% and a change in feed efficiency of 5-7% when using probiotic complexes (Kolechko *et al.*, 2023). Microbiome-oriented interventions could be reflected in productivity indicators through the enzymatic activity of probiotic strains and changes in the proportion of opportunistic microorganisms in the intestinal microbial profile. Information on combined interventions (immunoprophylaxis + probiotic) in model/related studies, where changes in oocyst excretion and productivity metrics were recorded, was considered separately and used as a mechanistic basis for explaining the potential synchronisation of immune and microbiome factors in control protocols (Table 2).

Table 2. *Predicted changes in piglet health and productivity indicators with the introduction of probiotics and prebiotics*

Indicator	"Before" status (control/no intervention)	"After" status (introduction of probiotics/prebiotics)	Effect interval according to sources (estimate)
Average daily gain, g/day	Baseline (according to the design of a specific study)	Increase relative to control	+8-12% (depending on the protocol/complex)
Feed conversion (kg of feed/kg of gain)	Baseline	Decrease relative to control	-5-7% (change in feed efficiency)
Frequency of diarrhoea syndromes in risk groups	Baseline in the risk group	Decrease in frequency after correction of the microbiome/resistance	-15-20% (as a clinical indicator in the protocols used)
Height of villi in the small intestine, μm	450 ± 35	520 ± 40	+15.6% ($p < 0.05$)
Indicators of non-specific resistance (e.g., phagocytic index)	Baseline	Increase after implementation of comprehensive programmes (where data available)	+20-30% (according to the ranges given in the sources)

Note: *predicted changes were formed as an interpretation of quantitative effects and reflected a "control/experimental" or "before/after" comparison within specific studies; actual values may vary depending on the age of the animals, diet composition, husbandry technology, and background epizootic pressure*

Source: *compiled by the authors based on A. Agazzi et al. (2020), N. Begma (2023), A. Kolechko et al. (2023), I. Klikin et al. (2024)*

The data in Table 2 summarised the effects of probiotics/prebiotics in the format "functional link – expected indicator – magnitude of change" and showed that the most consistently reproducible outcomes in different protocols were productivity metrics and feeding efficiency (an increase in average daily gains within +8-12% and a decrease in feed conversion by 5-7%). The morphometric indicator of the mucosa (villous height in the small intestine) in the protocol increased from 450 ± 35 to 520 ± 40 μm (+15.6%; $p < 0.05$), reflecting a statistically significant change in the morphometric indicator. A decrease in the frequency of diarrhoeal syndromes in risk groups was considered a clinical outcome reflecting the cumulative effect of colonisation resistance correction and metabolic activity of the microbiome. At the same time, indicators of non-specific resistance (in particular, the phagocytic index) were interpreted as contextually dependent indicators: their increase was more often described as part of complex programmes (a combination of immunoprophylaxis and probiotic interventions).

Practical recommendations for implementation in farms in Southern Ukraine

The recommendations are formulated as an applied protocol for the prevention and control of coccidiosis, combining risk-oriented diagnostics, biotechnological interventions (vaccination, immunostimulation, probiotics and prebiotics) and veterinary and sanitary measures with quantitative assessment of effectiveness. Implementation of the protocol is advisable provided that the epizootic situation on the farm is standardised, critical periods for piglets (farrowing, weaning, episodes of high temperatures) are planned, and "before/after" indicators are compared to monitor the effectiveness of the measures taken. For monitoring purposes, it is recommended to determine baseline and control values for infestation and/or oocyst excretion intensity, frequency of diarrhoea syndromes in piglets, average daily weight gain and feed conversion.

Control points should be coordinated with the production cycle: baseline indicators should be recorded before the protocol is launched, and repeat indicators should be recorded after the initial implementation cycle and subsequently at intervals that allow for comparison of batches under comparable technological conditions. To confirm the pathogen, coprological methods and/or molecular genetic tests can be used, depending on the availability of laboratory facilities, and the results should be used to adjust the frequency of control and identify priority risk groups. Specific immunoprophylaxis, subject to the availability of appropriate preparations and approved internal regulations, should be integrated into the standard early rearing protocol, ensuring coverage of the entire litter and attachment to the first days of life of piglets in accordance with the manufacturer's instructions. The effectiveness of immunoprophylaxis should be assessed based on the dynamics of oocyst excretion and/or infestation, the frequency of clinical manifestations of enteritis or diarrhoeal syndromes, and indirect production indicators, including average daily gains and feed conversion, which allows changes associated with intestinal health to be distinguished from fluctuations in feeding and management.

Preventive correction of non-specific resistance should be planned taking into account periods of increased risk, which are determined by the technological calendar and temperature conditions in the premises. Immunostimulants should be used in sows during the pre-farrowing period, in piglets during weaning, and during periods of high temperatures when there is a tendency for an increase in the incidence of diarrhoea or a deterioration in productivity in risk groups. It is recommended to evaluate the effect based on the frequency of diarrhoeal syndromes, survival and culling rates, and, if possible, laboratory indicators of non-specific resistance in accordance with the internal control programme. Microbiome-oriented measures should be implemented as a permanent element of prevention for risk groups, with an emphasis on weaning, regrouping and transition to a different diet. It is recommended to introduce probiotics (in particular, based on spore-forming bacteria compatible with feed production technology) and prebiotics (e.g., mannan-oligosaccharides) into the feed in accordance with the feeding schedule, feed form, and manufacturer's instructions. It is advisable to evaluate effectiveness on a "before/after" basis at the batch or section level in terms of average daily gains, feed conversion and diarrhoea frequency, and, if possible, to additionally take into account indicators of the condition of the mucous membrane or markers of resistance used in the relevant control protocols.

Veterinary and sanitary measures should be considered a mandatory component of control, with increased emphasis during the warm season and during periods of intensive turnover of batches. It is advisable to ensure mechanical cleaning, washing and disinfection, control of litter and technological surfaces humidity, as well as adherence to the "all empty – all occupied" principle to reduce the persistence of invasive material between batches. It is separately recommended to organise systematic control of rodents as a possible mechanical factor of re-contamination of the environment, and it is advisable to monitor the effectiveness of the sanitary unit through changes in infestation and/or oocyst excretion and the frequency of diarrhoeal syndromes in subsequent batches under comparable technological conditions.

It is advisable to implement the protocol in stages, starting with a basic assessment of the epizootic situation and preparation of organisational conditions, including coordination of the sampling scheme and ensuring the temperature conditions for storage of biological preparations. After recording the baseline values, it is recommended to launch the key elements of the programme, combining immunoprophylactic measures for piglets with probiotic-prebiotic feeding support, as well as planning immunostimulation in accordance with technological events and temperature conditions. Further monitoring of effectiveness is recommended 2-3 months after the start, comparing "before/after" indicators for oocyst excretion or infestation, frequency of diarrhoea, average daily gains and feed conversion, after which it is advisable to adjust the intensity of individual measures based on the data obtained.

DISCUSSION

In this study, the control of coccidiosis caused by *Cystoisospora suis* for the conditions of southern Ukraine is interpreted as a multi-component task, where the clinical effect is determined not only by the action on the parasite in the body, but also by the intensity of repeated entry of invasive material from the environment and the state of the intestinal barrier during technologically vulnerable periods. The limited self-sufficiency of chemoprophylaxis is consistent with the empirical observations of A.A. Lara *et al*. (2022), where *C. suis* circulation in the farm persisted despite the prophylactic use of toltrazuril. In this study, this was interpreted as a manifestation of the fact that the pharmacological component mainly affects the endogenous phase of the parasite, while the exogenous phase (oocysts in substrates) can maintain invasive pressure during repeated contamination. The results of A.A. Lara *et al*. (2022) supported the conclusion that prophylactic regimens limited to chemoprophylaxis do not always ensure transmission interruption in intensive housing conditions, especially in the presence of moisture retention areas, high animal density, and fluctuations in hygiene discipline. Biotechnological tools in this study were considered not as a replacement for chemoprophylaxis, but as means that can influence other links in the process.

The summary by G.A. Albanese *et al*. (2018), based on poultry farming data, demonstrated the technological feasibility of vaccine strategies against coccidia as a group of parasites and showed that the targeted formation of a local intestinal immune response can be achieved with the appropriate drugs and administration protocols. For pig farming, direct transfer is limited, but a comparable source correlates with the conclusion of this study regarding the fundamental achievability of mucosal immunity management as a tool for the prevention of coccidial infections, provided that it is adapted to the biology *of C. suis* and production contexts. This study shows that under conditions of technological stress and temperature load, the stability of the intestinal barrier can modify the severity of diarrhoeal syndromes and, therefore, influence the clinical manifestation of coccidiosis. The systematisation of alternatives to antibiotics by H.T. Thong & H.V. Duc (2022) is relevant because it describes the mechanisms of competitive exclusion, immune modulation and barrier function support associated with enteropathologies. Unlike the authors' general framework, this study focuses on the operationalisation of such mechanisms through measurable outputs (frequency of diarrhoea, productivity metrics, mucosal morphometric indicators), which increases the applied certainty of the criteria for monitoring and evaluating effectiveness.

Clinical and practical generalisations by E.R. Burrough *et al*. (2025) highlighted the limitations of routine antibiotic use due to the risks of dysbiosis and antimicrobial resistance and emphasised the priority of strategies to support gut health and the animals' own immune response. In this study, these findings are specified for coccidiosis in piglets: while maintaining invasive pressure from the intervention environment, which exacerbates dysbiotic shifts or reduces colonisation resistance, may exacerbate diarrhoeal syndromes such as the leading clinical phenotype. Thus, the data of E.R Burrough *et al*. (2025) are consistent with the conclusion of this study on the advisability of shifting the preventive strategy towards stabilising the barrier function and resistance, rather than towards long-term medication in the diet. The strategic advisability of vaccine prophylaxis as a long-term tool for controlling parasitic diseases is substantiated by V.A. Sander *et al*. (2020), who emphasised the potential for reducing the overall burden of infections without constant pharmacological treatment. In this study, the authors' position is used to argue that the vaccine component (if technologically feasible) logically fits into control programmes aimed at reducing parasitological and clinical indicators in combination with hygiene and management.

Mechanistic data from F.U. Memon *et al*. (2022) (bird model) demonstrated the ability of *Bacillus subtilis* to modulate the microbiome under conditions of active *Eimeria* invasion, indicating the potential of probiotic interventions to maintain microbial balance during periods of parasitic load. In this study, these data were compared with the conclusion that productivity metrics and feeding efficiency may be integral indicators of the effectiveness of microbiome-oriented interventions in pig farming, although interspecies extrapolation requires caution. Applied evidence for *Bacillus* spp.-based alternatives to antibiotics is provided by Y. Cheng *et al*. (2021), who described the positive effects of fermented products on productivity and digestive health indicators. The generalisations obtained in this study about productive outputs as stable indicators of the effect of microbiome-oriented interventions are consistent with the data from Y. Cheng *et al*. (2021) on the evaluation of such interventions through quantitative production and clinical indicators.

The work of C. Zifan *et al*. (2023) demonstrated an approach using recombinant *Bacillus subtilis* expressing the coccidian antigen (SAG22). In this study, such solutions were interpreted as a promising technological direction for combining the probiotic component and antigenic stimulus; at the same time, the mechanistic effect of simultaneous modulation of the immune and microbiome links for pig farming requires separate confirmation in designs that include parallel direct measurements of the relevant indicators. In the prebiotics section, I.M. Youssef *et al*. (2024) described the positive effects of MOS on intestinal morphology and resistance indicators in model systems. In this study, these data were correlated with the use of mucosal morphometric indicators as operational indicators of barrier status and with the conclusion that nutritional interventions can increase mucosal resistance during periods of stress. For pigs, A. Lee *et al*. (2025) demonstrated the effectiveness of galacto- and xylooligosaccharides in manipulating the microbiota and improving intestinal architecture. This is consistent with the conclusion of this study on the relevance of prebiotics as a component capable of influencing the barrier and thereby indirectly modifying the course of enteropathies in risk groups.

For integrated systems in pig farming, L.M. Gómez-Osorio *et al*. (2025) (using proliferative enteropathy as an example) demonstrated the effectiveness of approaches combining vaccination, feed additives and management measures. The conclusions of this study are consistent with the authors' position on the practical feasibility of protocols, where different tools address different risk mechanisms: immune resistance, intestinal ecology, technological factors, and environmental contamination. Data from M. Delsart *et al*. (2022) showed that on alternative farms, hygiene and management can minimise the parasite load without intensive medication. For this study, this supports the conclusion that a veterinary and sanitary unit is a prerequisite, especially in regions with a risk of persistent invasive material in wet substrates. Additionally, E. Labussière *et al*. (2022) demonstrated a modification of the faecal microbiota and associated physiological/behavioural changes when *Saccharomyces cerevisiae* var. *boulardii* was used during heat stress. In this study, these data were considered relevant to the conditions of southern Ukraine, as they supported the thesis that temperature stress can be accompanied by changes in intestinal ecology, and that microbiome-oriented interventions may have practical significance during periods of high temperatures. Thus, the results of this study specified the above international observations for the conditions of southern Ukraine, where climatic factors and the microclimate of the sections create the preconditions for repeated invasive pressure and increase the relevance of integrated preventive solutions.

CONCLUSIONS

The study found that the climatic and microclimatic conditions of pig farms in southern Ukraine, in particular prolonged periods of high temperatures during the warm season combined with local moisture in the substrates, create conditions for accelerated sporogony and prolonged preservation of *Cystoisospora suis* oocysts in the environment. Under such conditions, repeated contamination of bedding and technological surfaces is maintained, and the invasive pressure in piglet housing sections increases due to insufficient drying between technological cycles. This justifies the need for a systematic, rather than episodic, approach to prevention, focused on managing the links "source of invasion – environment – susceptible contingent".

It has been shown that routine chemoprophylaxis in subtherapeutic regimens has fundamental limitations, as it does not eliminate the environmental reservoir of invasion and does not control re-seeding of the environment. Additionally, it has been taken into account that the prolonged presence of chemical anticoccidials may be accompanied by undesirable consequences for intestinal ecology and biosafety, in particular due to the modulation of the microbiome and microbiome-dependent components of resistance, selective pressure on antimicrobial resistance, and environmental aspects of the persistence of active substances in the manure-soil-water system. The combination of these factors makes it advisable to move from monostrategies to integrated control protocols.

A comprehensive biotechnological approach to the prevention and control of coccidiosis has been substantiated, combining immunoprophylactic, immunostimulatory and microbiome-oriented interventions with enhanced veterinary and sanitary measures aimed at reducing contamination and ensuring substrate drying. Vaccine strategies are interpreted as a tool for reducing invasive pressure through the formation of mucosal antigen-specific protection and potential limitation of oocyst excretion, immunostimulation – as support for non-specific resistance during critical periods of technological and thermal stress, and probiotics and prebiotics as means of stabilising intestinal ecology and barrier function. A limitation remains the lack of comparable field data on the effectiveness of individual commercial biotechnological products specifically against *C. suis* in pigs, which determines the need for further controlled trials of the protocol with parallel assessment of parasitological, clinical and productive indicators and economic feasibility. Prospects for further research lie in conducting controlled field trials of an integrated protocol for the prevention of *Cystoisospora suis* in farms in southern Ukraine with simultaneous assessment of parasitological, clinical, productive, microbiome, and ecological safety indicators.

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CONFLICT OF INTEREST

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Сучасні біотехнологічні рішення у профілактиці й контролі кокцидіозу поросят у свинарських господарствах Півдня України

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Анотація. Метою дослідження було теоретичне обґрунтування та розробка практичних рекомендацій щодо комплексного біотехнологічного підходу до профілактики захворювання, спеціально адаптованого до регіональних умов Півдня України. Матеріали опрацьовано методами теоретико-методологічного аналізу, системного та порівняльного аналізу, аналітико-синтетичного узагальнення, методу аналогії та методичного проєктування практичних рекомендацій. У результаті проведеного дослідження епізоотичний процес кокцидіозу поросят у господарствах Півдня України інтерпретовано як такий, що підтримується поєднанням довкіллєвого резервуару ооцист Cystoisospora suis та технологічно зумовленої повторної контамінації підстилки й виробничих поверхонь. Ключовими чинниками, що визначають інвазійний тиск у секціях утримання, визначено взаємодію мікроклімату приміщень із режимами зволоження/висихання субстратів у межах технологічного циклу, зокрема за тривалих періодів високих температур у теплий сезон і наявності локальних зон стабільної вологи. На цій основі профілактику описано як керування ланками «джерело інвазії – середовище – сприйнятливий контингент» із пріоритетом заходів, що зменшують персистенцію інвазійного матеріалу між партіями та обмежують повторне засівання середовища. Обґрунтовано межі застосовності монохімічних схем у системах, де зберігається довкіллєвий компонент передачі, а також окреслено ризики, релевантні для мікробіому, біобезпеки та екологічних наслідків тривалої присутності антикокцидійних засобів. Операціоналізовано критеріальну схему оцінювання втручань через узгоджений набір індикаторів, що відображають паразитологічний, клінічний та виробничий виходи. Запропоновано інтегрований протокол, що поєднує санітарно-гігієнічне керування контамінацією, біотехнологічні інтервенції і стандартизований моніторинг за принципом «до/після». Практичне значення полягає у можливості впровадження у господарствах Півдня України уніфікованого алгоритму профілактики та контролю з відтворюваним оцінюванням результативності й зіставністю ефектів між секціями та виробничими циклами

Ключові слова: епізоотичний тиск; вакцинація; мукозальний імунітет; пробіотики; антибіотикорезистентність