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BIOSECURITY OF FARM LIVESTOCK PRODUCTION SYSTEMS: THREATS, PRACTICES AND NEW TECHNOLOGIES

BIOASEKURACJA GOSPODARSTW PRODUKCJI ZWIERZĘCEJ: ZAGROŻENIA, PRAKTYKI I NOWE TECHNOLOGIE

Summary: *The article provides a comprehensive analysis of biosecurity in livestock production systems, conceptualising it as an integrated framework of technical, organisational, environmental and behavioural measures. It discusses major transmission pathways, principles of farm zoning and hygiene, disinfection practices, and the management of human, material and informational resources. The role of veterinary prevention, innovative technologies (including IoT, biosensors, and monitoring systems), and regional and sectoral disparities in biosecurity implementation is examined. Particular emphasis is placed on socio-economic and psychological determinants that influence compliance, including risk perception, trust in institutions, and financial constraints. The article also reviews tools for assessing biosecurity performance, including audits, scoring systems, risk-modelling approaches, and environmental monitoring. The conclusions highlight the need to integrate technology, education, management and public policy within the One Health framework, and stress the importance of strengthening biosecurity culture at the farm level.*

Keywords: *Abiosecurity, livestock production, disinfection, biological vectors*

Streszczenie: Artykuł przedstawia kompleksową analizę bioasekuracji w gospodarstwach produkcji zwierzęcej, ujmując ją jako system powiązanych działań technicznych, organizacyjnych, środowiskowych i behawioralnych. Omówiono kluczowe wektory transmisji patogenów, zasady strefowania i higieny, techniki dezynfekcji oraz zarządzanie zasobami ludzkimi, materialnymi i informacyjnymi. Przedstawiono rolę prewencji weterynaryjnej, nowoczesnych technologii (IoT, biosensory, systemy monitoringu), a także zróżnicowanie wdrożeń bioasekuracji między regionami i sektorami produkcji. Szczególną uwagę poświęcono czynnikom społeczno-ekonomicznym i psychologicznym warunkującym przestrzeganie procedur, w tym percepcji ryzyka, zaufaniu do instytucji oraz barierom finansowym. Artykuł opisuje również narzędzia oceny skuteczności bioasekuracji, w tym audyty, indeksy, modele ryzyka i monitoring środowiskowy. Wnioski podkreślają znaczenie integracji technologii, edukacji, zarządzania i polityki publicznej w ramach podejścia One Health oraz konieczność wzmacniania kultury bioasekuracyjnej w gospodarstwach.

Słowa kluczowe: bioasekuracja, produkcja zwierzęca, dezynfekcja, wektory biologiczne

Introduction

Biosecurity is a basis for the contemporary animal production, determining health state of herds, economic stability and food safety and public health [68, 165]. Its subordinate aim is to prevent introduction, preservation and popularization of pathogenic factors; it may be obtained via the set of organizational, technical and behavioural measures such as inspection of animal transportation, isolation of the new introduced individuals and cleaning and disinfection procedures [39, 132].

Structural and technological changes, as being observed in animal production sector during the recent decades – intensification, specialization and integration of the supply chains – have contributed to increase of epizootic risk [5, 73, 165]. The increased stocking density, abbreviation of production cycles, trade globalization and contacts between the populations of farm and wild animals are favourable for transmission of pathogens. The mentioned factors are especially important in the context of diseases with a big economic meaning such as African Swine Fever (SFA) or highly virulent pathogenic avian influenza (HPAI) which show the consequences of insufficient level of biological protection [66, 156]. It was demonstrated that the appropriate implementation of biosecurity procedures could reduce the risk of HAAI occurrences even by 50% [102, 121, 164] whereas in the case of ASF, the activities connected with animal transport, waste management and disposal of dead animals lowered the probability of introducing virus by ca. 33% [5, 102].

Biosecurity is working based upon three complementary pillars: bio-exclusion, bio-control and biocontamination [30]. In practice, it is classified into external biosecurity, concerning the limitation of the risk of introducing pathogens to farm (e.g. quarantine, control of access, disinfection of vehicles and

equipment [5, 88] and internal biosecurity, including procedures limiting transmission at the farm (e.g. systems "all-in/all-out", separation of animal groups, application of protective clothes) [34, 165]. In spite of the employment of the mentioned solutions, the level of their implementation remains highly differentiated between the regions and sectors of production [6, 39].

As responding to the limitation of the traditional definitions, the conception of One Biosecurity has been proposed: it would integrate the health problems of humans, animals, plants and environment and include it into the higher framework of One Health conception [99, 122]. According to the mentioned approach, the effectiveness of biosecurity is dependent on technical infrastructure as well as on the social-economic factors, including the awareness of the farmers, the risk perception, confidence in veterinary service, or advisory help availability and financial resources [89, 115].

Biosecurity is also the instrument, limiting the application of antibiotics what has a meaning in the context of the growing resistance of microorganisms [39, 165]. It has been demonstrated that implementation of WASH principles (Water, Sanitation, Hygiene - an area of development aid that ensures access to safe drinking water, adequate sanitation, and promotes hygiene) in combination with the biosecurity systems decreases the application of antibiotics even by 57% [72], At the same time, the development of modern technologies – IoT systems, environmental sensors, automation of sanitary processes, robotics and analytics of the data – facilitates creation of adaptive models of epizootic surveillance [93, 146]. Algorithms of machine learning allow assessing the impact of the particular practices on the risk of the disease incidence what supports the precise management of threats.

A lack of consolidated instruments of the risk evaluation is a significant limitation. The currently employed score systems, questionnaires and digital applications allow identification of gaps in security measures but their effectiveness is dependent on the local specificity [34, 39, 79]. In spite of the mentioned problems, biosecurity is one of the most effective instruments of reduction of economic losses, improvement of animal welfare and strengthening of the sustainable production [93, 106].

The aim of this paper is to present the current state of knowledge concerning biosecurity in animal production, with the special consideration of its effectiveness, the barriers to its implementation and role of the modern technologies in prevention, supervision and control of infectious diseases in perspective of conceptions: One Health and One Security.

Biological vectors in the animal production systems

In the farm, dealing the animal production (poultry, pigs, cattle) there are many channels for transmission of pathogens among which the significant role is played by biological vectors such as rodents, wild and synanthropic birds, flies of the *Diptera* order and external parasites. The mentioned organisms may transfer microorganisms mechanically as well as biologically, becoming a key element of epizootic chain (Table 1).

Mice and rats (*Mus, Rattus*) are one of the most important components of microbiological risk in the farm premises due to a high ecological flexibility, capability of penetrating the buildings, a short reproduction cycle and whole-year activity [19, 41, 71] They may act as mechanical vectors (transmission of pathogens on the hair, legs and via faeces) and as biological reservoirs, maintaining infections for a longer time. The conception of "sponge of pathogens" shows that rodents may accumulate pathogens from the environment and then, re-introduce them after rat extermination procedures [41, 71]. It was documented that *Mus musculus* and *Rattus norvegicus* excrete *Salmonella enterica* in faeces for many days, contaminating the farm environment [19, 35].

Rodents are a meaningful source of many zoonotic pathogens, *inter alia*, *Salmonella spp.*, *E. coli*, *Enterococcus spp.*, and encephalomyocarditis viruses (EMCV) [8, 19, 136]. In the case of *Leptospira spp.*, they play a role of biological reservoir, when contaminating the environment with their urine and increasing a risk of infection in animals and in humans [108]. Although there is a lack of evidence of biological reservoir settling of PRRS virus (pig reproduction and respiration system), rats and mice may transfer it mechanically between the premises [14]. Similar hypotheses concern the mechanical transmission of avian influenza virus (AIV) [152].

Rodents may also transmit internal eelworms (*Nematoda*) and external parasites (mites, fleas), acting as indirect link in their developmental cycle, inducing the immunological stress in farm animals [19]. The effective rat extermination, sealing of the objects and limitation of an access to feed may significantly reduce the epizootic risk [14, 96, 154].

Wild birds, especially nitrating species from Anseriformes orders (ducks, geese, swans) and Charadriiformes (mews, plovers) are the key AIV reservoir in the natural environment. They may, asymptomatically, transmit viruses on big distances, contaminating water, mud and farm-adjacent zones, with the increased frequency during the migration periods [43, 80, 147]. They constitute the essential element of global AIV circulation and generic rearrangement of virus [153, 166].

Predatory and necrophagous birds (*Corvus corone*, *Pica pica*) may participate in mechanical transmission – especially of HPAI H5N1 – as a result of contact with dead carcasses or contaminated faeces [56, 86, 147]. In turn, synanthropic birds such as sparrows (*Passer domesticus*), jackdaws (*Corvus monedula*) or pigeons (*Columba livia*) are easily adaptable to farm environment where they may contaminate feeds, water and manufacturing space. The presence of wild birds in radius of 500 m from farm premises increases the risk of H5 and H9 incidence in poultry [58]. The analyses of GIS (Chief Sanitary Inspectorate in Poland) confirm that the farms, situated near water courses and wetlands are by 1.6–2.4 times more endangered to penetration of viruses to production environment [158].

Flies (Diptera), the non-stinging ones (*Musca domestica*) as well as blood-thirsty species (*Haematobia irritans*, *Stomoxys calcitrans*) are important vectors of bacterial pathogens and, potentially, viruses. Their life cycle, strictly connected with the presence of organic matter, is favourable for contact with faeces, manure,

feed residues and litter what facilitates colonization by numerous microorganisms, having a zoonotic importance [26, 100, 157].

Microbiological studies have demonstrated that *Musca domestica* is a vector for a wide spectrum of pathogenic bacteria, including *Salmonella enterica*, *Escherichia coli*, *Campylobacter spp.*, *Listeria monocytogenes* and *Enterobacteriaceae* which may be transmitted mechanically on the body surface as well as inside the alimentary tract of fly [17] [64]. In the experiment carried out in the farm environment it was found that as much as 40–50% of the flies, exhibited to the contact with the poultry being contaminated with Salmonella enterica, were subjected to colonization during 48h [157]. In relation to viruses, genetic material of Rotavirus A and Bovine Coronavirus was detected in body of flies; however, there is a lack of evidence of their active participation in primary contamination; probably they act as mechanical vectors [21].

Factors, which increase the participation of flies as a vector, include lack of physical barriers (e.g. grids, air curtains), constructional leaks in the farm buildings and insufficient sanitary level (deposits of manure or feed residues). The field studies in Egypt have demonstrated that the numerosity of flies in the farm buildings is correlated with the level of humidity of the litter and accumulation of organic matter; farms with the worse sanitary conditions have several times higher concentration of flies [1].

The blood-thirsty species of flies, especially *Haematobia irritans* and *Stomoxys calcitrans*, have a special meaning in the context of biosecurity. The mentioned species when feeding the blood of farm animals, may transmit the haemotropic pathogens, bacteria and viruses. In the studies conducted at the dairy farms, the presence of *E. coli*, *Salmonella* and *Staphylococcus spp.*, was found what confirms their capability of transmitting microorganisms and of the potential participation in the transmission of blood-derivate diseases [139]. Moreover, it was demonstrated that *Stomoxys* may transmit bacteria from *Anaplasma*, *Theileria* and *Bartonella Geni* and also, certain RNA viruses in cattle and pigs, especially in the conditions of high stocking density and open management systems [16, 87, 98].

Mites, ticks and other ectoparasites are the important element of biological risk in the poultry, cattle and pig sectors. Red mite of poultry (*Dermanyssus gallinae*) is especially relevant as it causes serious economic losses in the intensive management of laying hens [130, 134, 151]. Its incidence leads to many economic losses, resulting from lowering of laying capacity, anaemia, decline of the gains in body weight and increase of stress behaviour of the birds. *D. gallinae* infestations are also connected with the deterioration of egg quality and increase of the hen mortality rate [140]. The discussed insect may transmit *Salmonella enterica*, *Chlamydia psittaci*, Newcastle virus and AIV [128, 132, 149]. It was found in the laboratory studies that the *D. gallinae* individuals infected with *S. enterica* were able to transit the infection to the birds via skin and surface contact what resulted in occurrence of symptoms of *fowl typhoid* [130, 140, 32]. A special attention should be paid to vertical transmission of the pathogens concerning the discussed species. The studies have demonstrated that *Salmonella Gallinarum* may be transmitted from the adult individuals to eggs and larvae of the mites what suggests the existence of stable reservoirs of microorganisms in the farm environment, even after periodical disinfections [131].

Apart from the poultry mites, the important group is constituted by synanthropic ticks and other arthropods, living inside the farms, situated at the vicinity of grasslands, pastures and forests. Ticks from *Ixodes*, *Dermacentor* and *Rhipicephalus* genus may act as reservoir and vector for bacteria from *Borrelia*, *Anaplasma* and *Rickettsia* genus, transmitting the pathogens between a wild fauna and farm animals. In the context of animal production, their meaning grows together with the observed warming of climate which is favourable for widening of the geographical range of ticks and prolongation of the season of their activity [7, 45].

The important ectoparasites include also lice (*Menopon gallinae*, *Lipeurus caponis*) and itch mites (*Knemidocoptes spp.*, *Sarcoptes scabiei*), causing stress, skin damages, anaemia, decline of laying capacity and the increased sensitivity to reinfections [60].

Interactions between vectors in the farms create multilayer networks of pathogen transmission, exceeding the simple scheme: "vector – host". The rodents play a double role: they are a direct reservoir of numerous pathogens and function as hosts for ectoparasites – fleas and lice – which may themselves transmit bacteria, viruses and parasites. Systematic reviews confirm a wide spectrum of ectoparasites connected with the rodents (13, 70). In consequence, each intervention directed to one type of vector may affect the dynamics of others, generating the secondary changes in the transmission networks.

Microclimate of animal stalls, i.e. temperature, humidity and ventilation and constructional features such as slots, not sealed air inlets or lack of physical barriers modulate directly survivability and rate of vectors' proliferation. *Dermanyssus gallinae* as well as flies reveal a strong developmental dependence on relative humidity and temperature what affects maintaining of their population and intensity of pathogens' transmission within the farm [36, 105]. The environmental conditions determine also a distribution of vectors in the building's space, becoming favourable for their accumulation in the warm, wet and poorly ventilated sites.

Additionally, the populations of vectors are characterized by a distinct seasonality which shapes a cyclical epizootic risk. Seasonal increases of the number of flies, mites and ticks in the warm months are correlated with the increased probability of epizootics incidence although the level of the effect is dependent on specificity of pathogen, species of vector and local environmental conditions [48, 76, 90]. The seasonal variability affects also the efficacy of biosecurity measures – the means, implemented outside the peak of vectors' activity may not ensure a full protection in the periods of the highest risk what stresses the need of planning the interventions based upon biological cycles of the particular groups of vectors.

Zoning of farms, sanitary procedures and disinfection

Zoning of the farm and rigoristic sanitary procedures constitute the basis for biosecurity systems, enabling limitation of the risk of introducing and spreading of pathogens. Zoning

Table 1. Insects and arthropods – pathogens, mechanisms of transmission and control measures

Group of organisms	Main species / examples	Transmit ted pathogens	Transmission mechanism	Epizootiological importance	Measures of biosecurity control	Sources/ References
Flies – Flying insects	*Musca domestica, Stomoxys spp.*	*Salmonella spp., E. coli, Campylobacter*	Mechanical transmission of pathogens on body and gastrointestinal system	High meaning; epidemiological bridge between manure, feeds and animals	Sealing of objects, inlet grids, traps, rotation of insecticides, keeping cleanness of manure	[163] [149] [157]
Blood-thirsty flies	*Stomoxys spp.,*	Haemotropic bacteria, *E. coli, Salmonella*	Mechanical-biological transmission, contact with blood, faeces, wounds	Medium-high importance in open systems, pastural conditions	Reduction of grazing, repellents, light traps, monitoring of population	[16, 98]
Poultry mites	*Dermanyssus gallinae*	*Salmonella enterica,* potentially other bacteria and viruses	Mechanical and biological transmission, including direct contact and vertical transmission	High meaning: they may be a reservoir of pathogens between production cycles	Chemical/thermal disinfection, sanitary breaks, population management	[130, 134] [32, 131] [161]
Synanthropic ticks and other arthropods	*Ixodes ricinus, Dermacentor reticulatus, Rhipicephalus spp.*	*Borrelia burgdorferi s.l., Anaplasma spp., Rickettsia spp.*	Biological transmission via saliva during feeding -	Moderate importance: they may act as a bridge between wild fauna and farm animals	Limitation of contact with wild fauna, protected feeds, repellents, protection of the external sides of the farm	[62, 74, 143, 145]
External parasites (lice, itch mites)	*Menopon gallinae, Lipeurus caponis, Knemidocoptes spp.*	*Opportunistic bacteria (Staphylococcus, Streptococcus)*	Indirect transmission – damage of skin barrier, immunological stress	Moderate meaning: deterioration of animal welfare and the increased sensitivity to infections	Disinfection of equipment, medical bath, rotation of means, animal hygiene	[60, 119]

consists in division of the farm into areas with a differentiated degree of biological purity [38, 66]. We can distinguish three zones: pure (animal stalls), dirty (areas of a high risk: arrival roads, sites of loading, storehouses) and buffer zone where the change of clothes and shoes, and disinfection take place [34, 39].

The key element of zoning is a Line of Separation (LOS), being a border between pure and dirty zone. Its exceeding requires introduction of the specified procedures: hand and shoe disinfection, clothing change or employment of dedicated cloths [46, 84, 102]. The conducted studies confirm that the correctly implemented LOS reduces significantly the transmission of pathogens, transmitted by humans and equipment, especially with the support of the appropriate infrastructure, i.e. cleaning and disinfection sanitary station (sluice), appropriate marking and one-direction traffic of the staff [66, 165]. The persistence of observing the principles is, however, dependent on the regular training and organizational culture [4, 116]. Introduction of written instructions and regular training may increase the observation of the principles even by 40% [6]. In spite of the appropriate design of the mentioned zones, video monitoring showed that 61.4% of infringements was connected with the incorrect exceeding of the separation line what confirms the necessity of the constant control [116]. In big farms, it is recommended to organize microzoning, that is, internal division of the buildings into sectors what limits the horizontal transmission of pathogens, including PRRS (porcine reproductive and respiratory syndrome), avian influenza or mycoplasmosis [6, 39].

Sanitary procedures are practical supplementation of zoning. They include a limitation of the access to farm exclusively to the authorized persons, running of the registers of entrances and exits, and the application of sanitary locks, facilitating change of clothing, bath and disinfection of shoes [66]. Disinfecting matts and baths require removal of mechanical contamination and regular change of solutions as to keep their effectiveness [18, 111]. Protective clothing and shoes should be used solely inside the pure zone; obligatory bath and clothing change may reduce the PRRSV dissemination risk even by 70% [132]. The principles of labour sequence are also significant as it limits the internal transmission [39].

Maintaining the manufacturing cycles in all-in/all-out system decreases additionally the loading of pathogens. The complete evacuation of the object, cleaning, disinfection and keeping the sanitary distance reduce significantly the incidence rate (morbidity) between the lots of animals if the discussed measures are performed in accordance with the procedures [83, 116].

Equipment and vehicles are one of the main sources of the transmission of pathogens, including ASF when the C&D (cleaning and disinfection) procedures are improperly applied [34, 66]. The transport vehicles should be subjected to cleaning and disinfection on the stands, equipped with the systems of wastewater drainage and the environmental protection. The entrance to the farm territory should be possible only via one controlled entrance with gate, sluice lock and wheel wash.

Automatic sprinkling and foaming systems increase the efficacy of decontamination [141]. C & D practices are, however, often insufficient – there was demonstrated a low percentage of the application of brushes and disinfectants and too short cleaning time (9). In the poultry sector, it was revealed that decontamination of lorries and cages did not always remove HPAI [67]. Models of transmission indicate also that even in the case of theoretical 100-% effectiveness of C & D, certain contacts between the farms may become the potential channels of transmitting the diseases [52].

Disinfection is a final stage of sanitary cycle and consists in elimination or inactivation of microorganisms after earlier removal of organic matter and thorough mechanical cleaning (Table 2). The aim of the discussed process is to reach the conditions being microbiologically safe for animals and the staff; it is one of the most important instruments of limiting the epizootic risk in animal production [39]. According to the guidelines of WOAH [160] and EFSA [44], it covers three stages: purification, cleaning and application of biocide in the appropriate concentration and time of contact [66]. The range of disinfection covers surfaces of buildings as well as equipment, clothing, transport containers and the entrance routes [34]. The efficacy is dependent on physical-chemical properties of the agent, temperature and humidity of the environment, material of the surface and the presence of organic matter [39].

The employed disinfectants include the following main chemical groups: chlorine and aldehyde preparations, quaternary ammonium compounds (QACs) and oxidants. Hypochlorites ClO_2 have a wide spectrum of activity but they lose efficiency at the presence of organic matter. Aldehydes are effective in relation to spores but they require caution due to the toxicity. QACs demonstrate the effectiveness in relation to Gram-positive bacteria and protective viruses; on the other hand, hydrogen peroxide, peracetic acid and ozone ensure quick effect and are suitable for misting and aerosol application [93]. Ozone in concentration above 100 ppm in the environment with the high humidity level inactivates effectively RNA viruses and protective viruses [129, 155]. Its application, requires, however, strict safety procedures due to its toxicity for people and animals.

The contemporary technologies support disinfection via utilization of thermal-chemical, aerosol, foam and ultrasound methods which increase the even distribution of the agents and its penetration into the hardly accessible structures (93). Chemical and ultrasound misting and ensures the uniform overage of the surface, UV-C inactivates effectively microorganisms in the air and on smooth surfaces, and foaming prolongs the time of the agent's contact and improves the penetration of slots [63, 77] [106]. Ultrasound techniques improve a removal of contamination in transport cases and containers [28, 155].

To limit the risk of selection of tolerant organisms, it is recommended to rotate the disinfectants between the production cycles, including the agents from different chemical groups [127]. In spite of the declaration of applying C&D in 79% of pig farms, as much as 46.9% of the employed solutions had the improper working concentration [92, 75] what stresses the meaning of the process control.

The efficacy of disinfection requires monitoring. ATP tests, cultures and biological tests allow assessing the reduction of contamination and identifying the errors [44]. The complex approach – mechanical purification, vacuum cleaning and chemical disinfection – may reduce contamination by 99.9% as compared to cleaning alone [39]. Biofilms are a special challenge; they reveal many times higher resistance; they require mechanical removal of settled substances and agents with the confirmed penetrability such as peracetic acid or glutaraldehyde [107, 125].

In response to the growing environmental requirements, the biodegradable and ecological agents become more and more meaningful; they are based upon biosurfactants, organic compounds and silver nanoparticles. They are characterized by a comparable effectiveness in relation to many pathogens at the lower impact on the environment and lower risk of resistance selection [97, 106].

Table 2. Stages of the process of complete disinfection of farm premises

Stage	Goal	Practices – methods
Sanitization / Preliminary purification	Removal of organic dirt (litter, faeces, feeds, sludge) – reduction of barrier for action of disinfectants	Sweeping, collecting, splashing before disinfection
Mechanical cleaning	Dissolving and removal of fats, biofilms, organic residues which protect microorganisms from disinfectant	Cleaning with warm water, high-pressure stream, brushes, detergents
Disinfection	Inactivation and removal of bacteria, viruses and fungi	Sprinkling, mist, foaming, application of oxidants, aldehydes, QAC, ozoning (in the air or water)

New technologies and their application in biosecurity

Digitization of farm processes is one of the most rapidly developing trends in the contemporary biosecurity (Table 3 and Fig. 1). Integration of environmental sensors, vision systems, analytical algorithms and instruments of IoT enables the constant supervision of production parameters and early detection of biological threats [66, 93].

IoT systems register temperature, humidity, ammonium and CO_2 concentration and other environmental indicators and the mentioned data are analysed at a real time [106]. It allows a quick identification of deviations from standards, which may be an evidence of irregularities in microclimate, ventilation failures or the beginning of disease processes. The studies from Denmark and the Netherlands revealed that introduction of the environmental sensors limited epizootic incidents by 23–30% [39].

Vision systems and analysis of image (computer vision) are employed in observations of animal behaviour, enabling early detection of apathy, lameness, disturbances in feed intake or changes in the rhythm of activity [97]. Integration with AI algorithms allows automatic classification of health incidents and generation of alerts for the staff. IoT technologies are the background of Precision Livestock Farming, combining the data from the environmental sensors and devices born by the animals (wearables) such as neckbands with accelerometers or thermometers [3, 101, 148]. Registration of temperature, activity, feed and water intake facilitates (*inter alia*, owing to the use of thermovision cameras) detection of deviations still before occurrence of clinical symptoms of disease [39, 95, 123]. Transformation from the reactive to pro-reactive approach – owing to the augmented analysis – allows anticipation of anomalies and optimization of prophylactic measures [3, 133].

The models based upon integration of AI, IoT and the sensors enables prediction of the risk of mastitis, avian influenza, PRRSV, monitoring of behavioral changes and prognosing of production declines [66, 165, 101]. Linking of the environmental sensors and herd management platforms allows the immediate informing of vet about the detected biometric or environmental deviations.

Big Data Analytics facilitates also modeling of pathogens' propagation, utilizing the data of GIS, animal flows and the environmental factors [106]. AI is also employed in biosecurity logistics when optimizing the transport routes, timetables of disinfection and traffic of the staff [39].

Progress in the field of biosensors and *in situ* diagnostics allows the transfer of laboratory analyses directly to the farms. Electrochemical, optical and micro-fluidal biosensors detect pathogens (*Salmonella spp.*, *Campylobacter spp.*, PRRSV, AIV) at a real time [97], with the reaction time amounting to ca. 30 minutes and without the need of sending the samples to laboratory [106]. Introduction of biosensors in poultry farms helped to detect the sources of salmonellosis by 4 days earlier, in average as compared to traditional microbiological methods [93]. LAMP (Loop-Mediated Isothermal Amplification) and CRISPR-Cas12a technologies ensure a high sensitivity and specificity with minimum equipment requirements [44, 106].

New biological technologies are a relevant supplementation of biosecurity systems. Bacteriophages are examined as alternative to antibiotics in control of zoonotic bacteria; enzymatic

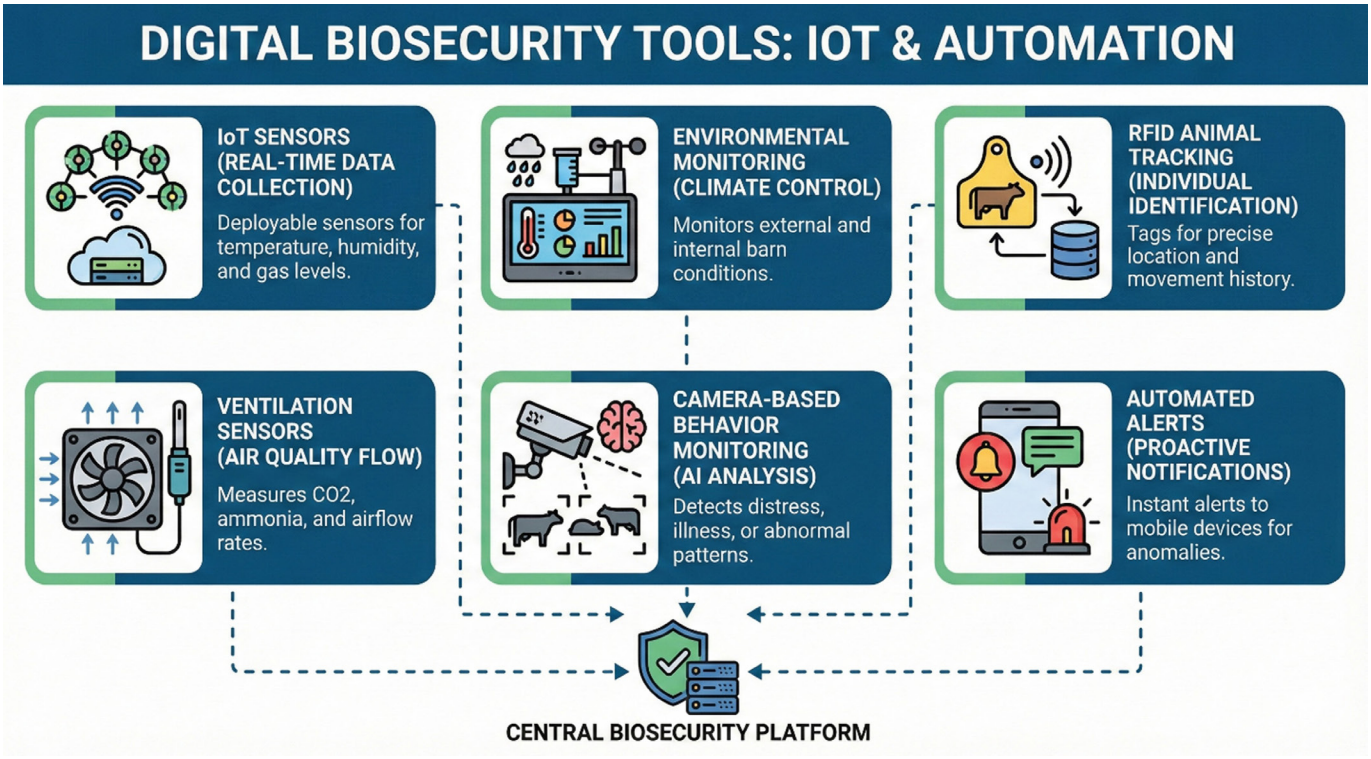

Fig. 1. Application of the new technologies in biosecurity of animal production

and probiotic biopreparations reduce ammonium and improve the sanitary state of the environment and nano materials such as nanoparticles of Ag, copper or ZnO, are utilized in disinfecting coatings]97, 106]. The nanotechnological coatings maintain 85-95-% reduction of Gram-negative bacteria for at least 6 months [66]. Bio-remediation technologies based on biofilter, algae and microorganisms support affluent treatment and reduce the emission of pathogens to the environment [93].

Cleaning robots, autonomic disinfection systems and UV-C equipment reduce the exposure of the working staff to pathogens and limit the mechanical transmission [66]. Mobile robots as equipped with misting devices or UV-C modules (λ = 200 – 280 nm) disinfect the surfaces and the air space, reducing the microbiological contamination of the air (bacteria, viruses, fungi) from 92% to 96.8% [55, 165]. Effectiveness of disinfection of this type is dependent on the irradiation rate, exposure time and distance from the light source [27, 55]. In literature there were described the prototypes of robots combining the UV-C action and H_2O_2 aerosols, controlled by the environmental data and utilizing SLAM (Simultaneous Localization and Mapping) algorithms and ROS (Robot Operation System) in autonomic navigation [29, 162]. The mentioned systems enable disinfection of hardly accessible areas and dynamic adaptation of the intervention intensity to the risk level. Prototype of "Mobile Robot + IoT" combined the environmental sensors (humidity, pH, temperature) and the driven disinfecting robot (UV + ozone) in poultry house [81]. To optimize the routes, metaheuristics such as PSO (Particle Swarm Optimization), GOA (Grasshopper Optimization Algorithm) or WOA (Whale Optimization Algorithm) are employed; they ensure the complete coverage of the area at minimum time of exposure and low risk of collision [112].

Labour safety with UV-C irradiation is a significant problem. Due to its toxicity for human tissues, especially of eyes and skin, the discussed systems must work in "no-service" mood, with the application of the presence sensors, safety barriers and automating switching oof in the case of detecting the movement of man. Due to these reasons, UV-V robots are considered as the supplementation of the standard cleaning and disinfection procedures [55, 112].

Radiant Catalytic Ionization (RCI) generates reactive forms of oxygen (ROS) such as hydrogen peroxide and hydroxyl radicals which reveal a strong biocidal effect. The studies demonstrated the reduction of pathogens (*E. coli*, *Enterococcus faecalis*, *S. aureus*, *Listeria monocytogenes*) exceeding 99% [137] and the efficacy grows together with the reduction of organic matter and prolongation of the exposure time [138]. RCI systems reduce also ammonia and dust concentration in the premises [104] and increase the effectiveness of wastewater and manure treatment (elimination of E. coli, Salmonella, Listeria and moulds) in combination with aeration [57].

Photocatalytic technologies with the application of titanium dioxide (TiO_2), activated by UV light (or the visible light after modifications) are intensively tested as the methods for air and surface disinfection in the livestock breeding environments [50]. The review of photocatalysis techniques stresses that the appropriate structure of material (anataz, rutyl) and the lighting and humidity conditions have the crucial impact on the efficacy of the process [31]. In the systems of photocatalytic gates,TiO_2,

Table 3. New technologies in biosecurity – advantages, limitation and recommendations

Technology	Principle of acting/ Application	Advantages	Limitations and risks	Implementing recommendations
Radiant Catalytic Ionization (RCI)	Generation of reactive oxygen ions and peroxides; air ad surface disinfection	Reduction of bacteria and fungi in the air; lowering of ammonia and odour concentration	Risk of ozoning; necessary control of concentration and air flow	Installed in ventilation channels; periodical calibration and validation of efficiency
UV-C and disinfecting robots	UV-C irradiation of 200-280 nm inactivates DNA/RNA of pathogens	High efficacy (up to 96%); automation; lack of chemical residues	Risk for people and animals; lack of penetration in shade sites	To be applied after preliminary treatment; automatic safety sensors; mapping of routes
IoT and environmental / biometric sensors	Network of sensors: activity, temperature, feed intake, gases, humidity	Early detection of behavioral changes; data for prediction models	Costs and maintenance of system; analysis of a huge quantity of data	Integration with alert applications; trends' analysis; remote veterinary supervision
Autonomic disinfecting systems (AGV, ROS, SLAM)	Mobile robots with foaming device or disinfecting mist; self-navigation	Constant, uniform disinfection; minimization of human participation	High cost; necessary mapping of objects; collision risk	Pilotage tests; integration with the timetable of treatments; automatic logbook

AGV – Automated Guided Vehicles; SLAM – Simultaneous Localization and Mapping; ROS – Robot Operating System

modified with Cu^{2+} ions, reaching more than 99% reduction of bacteria (*Salmonella enterica*, *Staphylococcus aureus*, *Enterococcus faecalis*) is applied. There is also observed a decline in respirable dusts by 8-31% what may limit the infectious aerosols [91].

Management in biosecurity systems

Effective biosecurity in animal production farms is based, inter alia, upon coordinated management of human, material, logistic and information resources (Table 4). All the mentioned elements commonly decide on the level of biological protection, determining the epizootic risk and health stability of the herds.

Management of pests in animal production, covering rodents, insects and synanthropic birds, is the integral element of biosecurity. Effective programs require the integrated approach (Integrated Pest Management, IPM) combining the preventive measures (sealing), systematic monitoring and mechanical, biological and chemical interventions. In poultry, pig and cattle farms, IPM program should have a multi-level form, considering organizational means as well as constructional protection of buildings which are the first line of protection against penetration of the pests to farm premises and feed storehouses [23, 47, 12].

Sealing of infrastructure is a basis for prevention. The buildings should be free from slots, exceeding 0.6 cm for mice and 1 cm for rats; any openings – at the doors, windows, cables, pipelines or ventilation inlets must be protected with the materials resistant to biting, such as steel, metal grids of cement mortar. The constructions endangered to penetration such as wood, thin plastics or insulation layers do not meet the biosecurity requirements. It is also recommended to deepen foundation at minimum of 0.5 m and apply the concrete bands around the buildings which make drilling of the holes by rodents difficult [15].

Environmental measures, including keeping the order around the buildings, have the crucial meaning for limitation of the availability of feed and hiding sites for the pests. Regular removal of organic wastes, feed residues and waste landfills reduces the feed resources, attracting rodents and insects. Trimming of vegetation eliminates the site of asylum and migration channels and the storage of feed in hermetic, biting-resistant containers, preferably metal silos, placed on elevated sites, limits the risk of contamination. Systematic cleaning and disinfection of feed tables, feeding line and storehouses reduce the microbiological pressure and eliminate the sources, attracting flies [22, 59, 82]. There is a necessity to minimize the nooks and corners, seal the cable and pipeline passage, and to apply smooth finishing

Table 4. Risk factors and preventive measures in management of feed, water and wastes

Obszar	Risk factor/contamination source	Mechanism of transfer/consequences	Preventive measures/corrective steps
Feed	Microbiological infection (*Salmonella*, *E. coli*, *Clostridium*)	Infections of gastrointestinal system, intoxication, environment contamination	Purchase of feed from certified suppliers; microbiological control of lots, disinfection of silos and containers
	Presence of mycotoxins (DON, ZEA, OTA, AF, FUM)	Immunosuppression, reproduction disturbances, decline of production performance	Toxicological tests; application of adsorbents' drying of grain; FIFO; heat treatment
	Improper feed storage	Development of moulds and aerobic bacteria	Ventilation and drying of storehouses; regular treatment; lack of contact with rodents and birds
Water	Biological contamination (*E. coli*, *Salmonella*, *Leptospira*)	Faecal-oral transmission of pathogens; infections in animals	Microbiological tests (every 1 – 3 m); chlorination, ozoning, UV; closed-type reservoirs
	Biofilm in drinking installations	Reservoir of bacteria; loss of disinfection effectiveness	Regular flushing of line; disinfection with hydrogen peroxide or ozone
Wastes	Incorrect storage of manure and feed residues	Dissipation of pathogens, odours, insects, rodents	Hardened, roofed storage places; distance min. 50 m from dairy barns; separation of zones
	Incorrect disposal of dead corps	Source of infections; attracting the predators	Hermetic containers; receipt by the authorised units; disinfection of the equipment after transport
	Effluent contamination	Pathogens in surface water	Retention reservoirs; lack of flowdown to water intakes; farm effluent treatment

DON – deoxynivalenol; ZEA – zearalenone; OTA – ochratoxin A; AF – aflatoxins; FUM - fumonisins

materials. Regular structural inspections, i.e. assessment of slots, cracks and installation passages, enable early detection of infestation sources. Documentation of the traces of the pests' presence (faeces, chewing traces, fragments of nests) allows a quick reaction and planning of further measures. Registers of traps and results of observations are the basis for evaluation of the efficacy of intervention and facilitate planning the rotation of the methods and counteracting the behavioural adaptation or resistance to the chemical agents [11, 20, 78].

The control methods include three groups of the measures. Mechanical methods – mechanical traps, rat extermination with poison, sticking-adhesive traps and barriers, are used in the case of limited infestations or when the application of chemicals is undesired. Biological methods employ natural enemies of the pests such as owls, cats, parasite insects and microbiological preparations or fungi, being pathogenic to insects. Chemical interventions, including rodenticides and insecticides, are employed exclusively in the case of strong infestations and with the preservation of rotation of active substances, safety principles and veterinary regulations [23, 25]. Rat extermination should be planned, based on monitoring and cyclic evaluation of the efficacy. In practice, a significant role is played by the environmental parameters: dry litter, efficient ventilation and control of temperature and humidity which decrease the attractiveness of the premises for insects and mites [47, 117].

Management of personnel is a foundation of the system as the competences, awareness of threats and consequence of procedures' application by the employees determine the effectiveness of implementation of procedures [39, 66]. The management of the discussed area covers choice of the staff, cyclic training, clear division of duties, monitoring of observing the principles and constant improvement of skills [38, 165]. Coherence of the measures increases the nomination of the person responsible for the supervision of procedures and biosecurity documentation [6, 132].

Training of the employees should include practical knowledge concerning mechanisms of pathogens' transmission and the risk assessment as well as practical skills connected with the disinfection, work in clean and dirty zones and the application of personal protection agents [93]. Training programs play a key role in this respect; in Belgium and the Netherland, the participation of the farmers in training increased the percentage of farms with a high level of their implementation from 48% to 79% during 2 years [38, 39]. The most effective trainings combine the practical knowledge and motivation component, emphasizing the measurable economic and environmental profits. Effectiveness increases additionally when the education is connected with the veterinary advisory activity and instruments of financial support [122, 159]. The regular audits, motivating systems and effective communication between the management and the staff decrease the risk of errors and formal procedures of informing about incidents facilitate a quick identification of gaps and implementation of corrective measures [38].

The integrated management of resources combines the activities concerning the people, infrastructure and information flow in the coherent system, limiting the epizootic risk (38, 165). The mentioned approach requires utilization of risk analysis instruments (Risk-Based Management) which enable prioritization of procedures in accordance with the potential health and economic consequences [39]. Mathematic models and digital models of dissipation of pathogens support prognosing of the threats and optimization of distribution of biosecurity resources [93, 106].

Material resources include infrastructure of buildings, disinfectants and protecting agents, equipment, feeds and water which must be constantly available in order to ensure the continuity of biosecurity actions [39]. Monitoring of resources and planning of supplies has a special meaning in the epizootics periods when the material deficits may lead to critical disturbances (66). From the perspective of biosecurity logistics it is crucial to supervise transport of animals, feeds and wastes. The principle of biosecure logistics assumes that each vehicle entering the territory of the farm must be cleaned and disinfected and its route should omit the clean zones [93]. High-productive farms employ widely the electronic systems of transport registration what allows traceability of the materials' origin and reconstruction of potential routes of pathogens' transmission [106, 165].

Planning of logistic resources should be based on the risk analysis and include the assessment of transport roads, distribution of disinfection points, localization of feed and manure storehouses and readiness to introduce the contingency plans in the case of contamination occurrence [38].

Quality of feeds has a key meaning for biosecurity. The feeds must derive from the certified suppliers, with the microbiological control and the appropriate documentation. The contamination with bacteria (*Salmonella spp.*, *E. coli*, *Clostridium perfringens*) and mycotoxins is a significant threat to health. The conducted studies revealed that even the subclinical accumulated levels of mycotoxins: deoxynivalenol (DON), zearalenone (ZEN), ochratoxin A (OTA), may negatively affect the health, reproduction and dairy performance of cows [113, 4]. Limitation of the risk is supported by keeping the humidity of feeds <14%, application of a new system FIFO (first-in, first-out), regular cleaning of silos, application of mycotoxin adsorbents (e.g. bentonite, zeolite), biological additives (enzymes, yeasts, probiotics) and heat treatment (pelleting, extrusion). Austrian analyses have confirmed that feed management is connected with the udder health, reproduction and milk production parameters [113].

Water is one of the main routes of pathogens' transmission, especially via faecal-oral mechanism. It may be a source of Escherichia coli, Salmonella, Leptospira or Clostridia and intestinal viruses. The risk is increased by the formation of biofilm in installations what protects microorganisms [114]. The examination of 105 drinking bowls in 24 German dairy farms revealed the presence of, *inter alia*: *E. coli* and MRSA (Methicillin-Resistant Streptococcus aureus) in biofilm [61]. The effective disinfection of installation requires designing with the possibility of flushing, mechanical treatment and application of chlorine-based agents, hydrogen peroxide, ozone or silver ions. The efficacy is dependent on the level of organic contamination

and physico-chemical parameters of water [65]. Hydrogen peroxide (H_2O_2) in concentration of 50–200 ppm reveals a high effectiveness in relation to heterotrophic bacteria under the condition of time > min. [135]. Ozone-employing technologies eliminate effectively Gram-negative bacteria and RNA viruses in water and effluents, at a high humidity and uniform distribution (24, 69). A regular microbiological monitoring (every 1- 3 months) should include determination of total bacteria count (as CFU, colonies-forming units), *Enterobacteriaceae*, and bacteria from *coliforms* group as well as periodical tests of *E. coli* presence as indicator of faecal contamination. Design of installations without "dead" segment and protection of reservoirs from the access of birds and insects is a significant element of limitation of the recontamination. In the studies of broiler farms, biofilm in water installations was a meaningful reservoir of antibiotic-resistant microorganisms, being a threat to health of humans and animals [114]. Wastewater and flush water coming from cleaning of premises and equipment cannot be drained to manufacturing zones or to usable water without treatment [122].

The integrated measures in respect of water hygiene and treatment (WASH + biosecurity) in the European farms led to reduction of microbiological load and decrease of antibiotics' application even by 57%. The analyses showed that the sanitary interventions, especially cleaning of drinking line and improvement of water sanitary state brought profits in ca. half of the cases, reducing intestinal diseases and decreasing the use of antibiotics [72].

Dead animals must be immediately isolated and transferred to separate, under-roof located, hardened and marked storage places, being situated far from the farm buildings. According to the Regulation (EC) no 1069/2009 [110], their disposal must be carried out by the authorized entities and transport must be implemented in hermetic, disinfected containers or especially dedicated vehicles which are subjected to registration and recorded entries in the disinfection books. Organic wastes – manure, litter and feed residues, should be stored in the fenced sites at the distance of at least 50 m from the premises, with the consideration of the risk of surface flowdown. Composting or methane fermentation (≥55°C for few days) are the effective methods for inactivation of many pathogens [33, 51].

In respect of meaning, information management is the equivalent element of biosecurity system, comparable to supervision of human and material resources. The data concerning animal heath, results of the tests, disinfection control, personal movement and utilization of resources are the basis for the risk assessment and enable undertaking the operating and strategic decisions [39]. The effective system covers three crucial components: collection of the data, their analysis and archiving [66, 165].

Introduction of digital biosecurity-supporting instruments facilitates automatization of processes and elimination of the errors, resulting from the manual operations. More and more frequently, there are used technologies of IoT (Internet of Things) and RFID (Radio-Frequency Identification), enabling automatic monitoring of traffic of people, vehicles and materials in the real time [97, 106] The mentioned solutions allow a quick detection of the procedures' infringement, identification of the threat sources and limitation of the errors, resulting from human factor.

Biosecurity documentation includes registers of entries and exits, timetables of cleaning and disinfection, records of the use of chemical agents, results of laboratory tests, reports from audits and information about incidents connected with the biosecurity (38). Keeping the documentation currently and completely is the evidential basis in administration control and, as the same time, it facilitates the retrospective analysis of events in the case of disease outbreak occurrence [66].

Empirical evidences confirm the effectiveness of digitalization of the documents. In the studies carried out in the poultry farms in Belgium and Germany, there was recorded a reduction of the procedural errors by 32% during the first year from the implementation of digital registration systems [39]. Introduction of digital solutions abbreviates time of audits, increases the transparency of processes and makes the integration with the national systems of veterinary supervision easier.

Regional diversification and sectoral implementation of biosecurity

The level of introducing the biosecurity principles is not uniform in all the sectors (Fig. 2). The highest level of conformity is observed in pig and poultry production where the epizootic pressure and market requirements are the highest ones [6, 39]. In pig production, the advanced biosecurity systems include the strict control of animals' movement, quarantine, disinfection of equipment and vehicles, access barriers and protective clothing [5, 66]. Farms which maintain age segregation are characterized by a lower morbidity rate [165].

In poultry sector, we may observe a high degree of biosecurity organization. The example may be Italian turkey farms where the level of compliance with sanitary protocols is high [150]. The challenges still concern maintain the sanitary lock zones, hygiene of the staff and the proper waste management [89]. In the small-scale farms, such as household henhouses, the level of biosecurity is very low what is a serious threat to the total sector [40].

In the dairy farms, the key risk area includes milking hygiene and cleaning of dairy equipment. Improper practices are favourable for development of *Staphylococcus aureus* and *Escherichia coli* [144]. Purity and dry microclimate in the animal stalls are also meaningful because they reduce incidence of infection of cow udders (*mastitis*). The level of implementing the principles in dairy cattle sector is highly differentiated – the countries such as Denmark or the Netherlands keep high standards owing to obligatory audits and certification programs such as BVD-free or John's Control [120] whereas in the extensive management systems, the basic practices are sporadically introduced.

In the sheep, goat and rabbit sector, the introduction of biosecurity principles has a score system and is often limited to minimal requirements [165]. In Portugal, the level of introducing the biosecurity in farms, keeping small ruminants is low, especially in respect of the run of cleaning, disinfection and quarantine. The

low level of biosecurity results from the ageing of the farmers, limited financial resources and lack of consolidated procedures [6]. Due to low production concentration and extensive systems, the threat of pathogens' transmission is lower, however, the risk of the contact with the wild disease reservoirs is increased [121].

In fishing and aquaculture, the implementation of biosecurity is dependent on the scale and type of production. Intensive management farms employ the systems of filtration and disinfection of water and quarantine of the fry whereas the extensive farms are based mainly upon the control of the origin of the stocking material [44].

The level of introducing the biosecurity principles in the animal production farms reveals a considerable regional variation, resulting from the environmental conditions, production structure and available economic and organizational resources [38, 39]. The key determinants include livestock level, model of farm property, level of industrialization of production, availability of technical infrastructure and power of administration regulations [66]. The comparability analyses indicate that the highest level of compliance with the biosecurity principles is recorded in the countries, having the developed agricultural infrastructure at their disposal whereas the small, extensive farms, functioning in the conditions of limited resources are characterized by a lower level of implementation of the discussed principles [6, 40].

In the European Union, the level of observing the principles of biosecurity is differentiated: the average level of complexity is assessed at 66.9/100 and only 58% of poultry farms implement a full set of the required procedures [103]. In Sweden, as much as 43% of the pig producers have not implemented the recommended procedures [118].

In the North Europe, especially in Denmark, the Netherlands and Germany, the biosecurity systems are strongly formalized and integrated with the national veterinary supervision. They include obligatory audits, digital registers of transport, control of access and standardized procedures of cleaning and disinfection [93, 165]. The high level of the compliance results from the multi-year sectoral programs and a close cooperation of administration and producers. A different situation is recorded in the Southern and Eastern Europe *(inter alia*, Poland, Rumania, Bulgaria) where the biosecurity practices are heterogenic what results from the disintegration of farms' structure, economic limitations and uneven access to modern technologies [39]. EFSA data of 2021 show that the compliance with the basic requirements of biosecurity in poultry sector was equal to 42% in the east region and 86% in the north-west region. In Poland, the intensification of implementing the principles of the biosecurity was directly connected with the incidence of ASF and AUV [53].

In the regions with the high production concentration such as the northern France, the Netherlands or Flanders, there are the integrated systems of regional biosecurity management, based on the common instruments of epidemiological supervision and standardization of the procedures of transports' disinfection (93). The mentioned solutions limit the transmission of pathogens between the farms and improve the intervention measures.

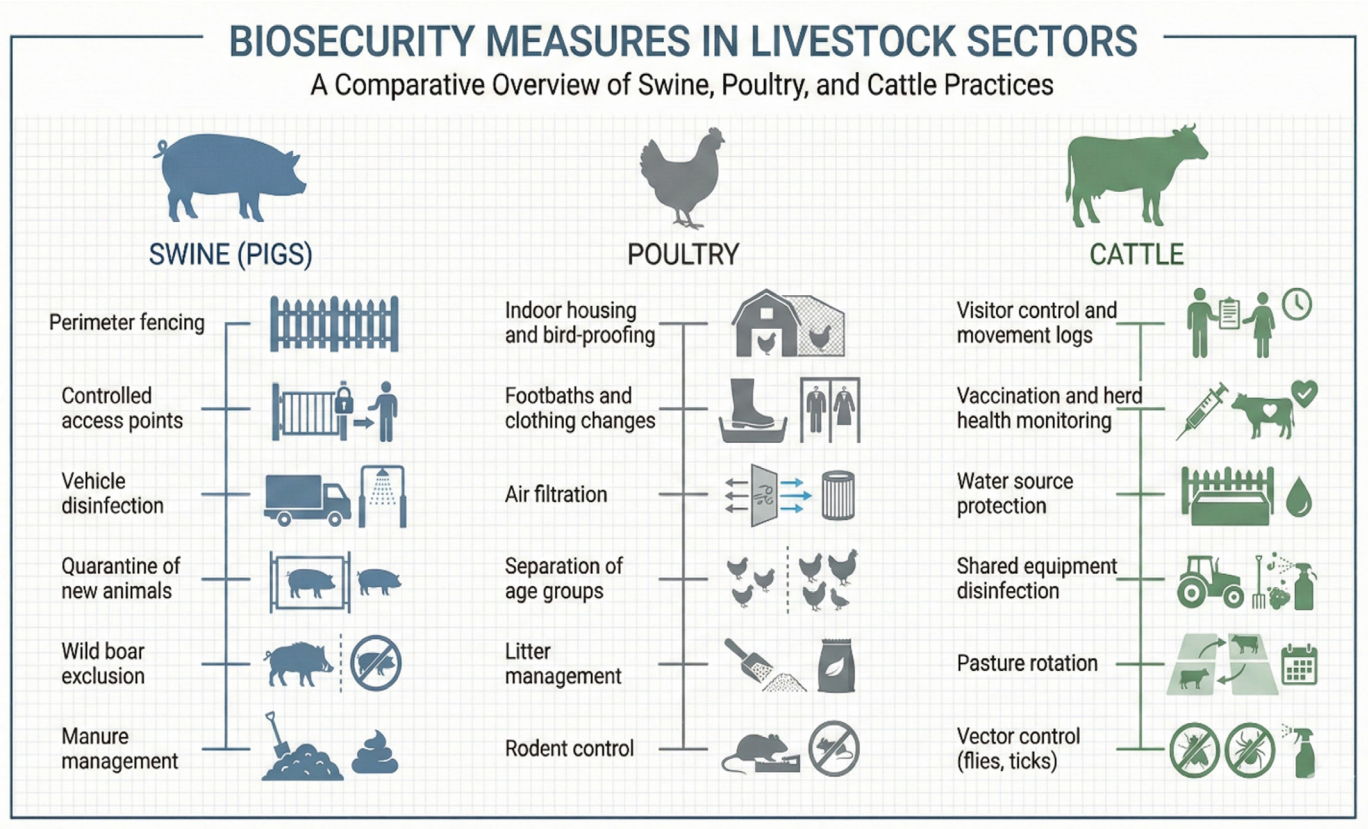

Fig. 2. Biosecurity – comparison of the most important practices in the particular sectors of animal production

Veterinary prevention in the biosecurity systems

Monitoring of the health state of the herds and constant veterinary supervision are the significant elements of the effective biosecurity. They facilitate early detection of pathogens, assessment of the effectiveness of prophylactic measures and quick introduction of intervention. Veterinary prevention covers the steps oriented to preventing the infectious diseases, their early recognition and minimization of the consequences coming from the potential sources [38].

The main aim of the preventive measures is to keep the population resistance, limit the transmission of pathogens and reduce the demand on antibiotics, in compliance with the principles of responsible management of animal health [5]. Veterinarian is responsible for development and supervision of prophylaxis program, running the diagnostics, epizootic monitoring, assessment of implementation of the biosecurity principles and advisory activity in respect of animal hygiene, nutrition and welfare [39, 165]. The regular audits, updating of procedures and cyclic training of the staff are the elements of the discussed procedures.

Vaccinations are the fundamental pillar of veterinary prophylaxis and constructing the population resistance. Their effectiveness requires correctly planned program of immunization, adapted to the health state of the herd, local conditions and production system [39, 66]. In pig production, vaccinations against PPV, PRRSV, *Erisipelothrix rhiusopathiae*, *Mycoplasma hyopneumoniae* and *Lawsonia intracellularis* are employed [5, 83]. In the poultry sector, vaccinations against ND, IBV, IBDV, AIV and colibacteriosis [39] have the crucial meaning, and in the case of cattle production – vaccinations against BVD-MD, IBR, PI3 and leptospirosis have the highest importance [66].

The effective vaccination program is based upon the collective resistance and the level of vaccination exceeding 80% reduces significantly the horizontal transmission [165]. The evaluation of immunization efficacy requires monitoring of the antibodies' level and seroconversion as the lack of such assessment may lower the real protection even by 25% [6].

Diagnostics is a key element of the early detection of threats and assessment of the effectiveness of biosecurity measures [66]. Epizootic monitoring facilitates tracking of dynamics of pathogens and a rapid response to occurring disease sources [39]. Depending on the species, the serological and molecular tests, based upon qPCR, LAMP and ELISA, allowing detection of pathogens in clinical and environmental samples, are employed [93, 106]. Development of mobile diagnostic platforms and biosensors enables performance of analyses in situ, abbreviating time of reaction [106].

Regular PCR and serological tests are indispensable for detection of subclinical infections. The studies of the cattle revealed the effectiveness of multiplex qPCR methods in the simultaneous detection of many pathogens of respiratory system [54]. Documentation of disease incidents, covering symptoms, diagnosis, treatment and the result, facilitates analysis of health trends. Registers of vaccinations, diagnostic tests and sanitary procedures are the basis for evaluation of the system's efficacy [42]. The results of molecular monitoring and analysis of health registers function as indicators of biosecurity effectiveness. The study of Scollo et al. (2022) revealed that the systematic monitoring of biosecurity in 15 pig farms had the impact on reduction of lung changes at slaughter [132].

Choice of the appropriate KPI (Key Performance Indicators) parameters allows a systematic monitoring of the herd health state and effectiveness of the procedures. They include, inter alia, the number of the disease cases per 1000 animals/year, time from the symptoms to isolation, the level of seroconversion, the results of PCR tests of symptom-free animals, reproduction indicators and operating parameters. In the studies concerning the dairy farms, as many as 34 key indicators of reproduction evaluation were distinguished [10].

Limitation of the application of antibiotics is one of the crucial aims of the contemporary veterinary prevention; it may be carried out via implementation of prophylactic strategies which allow maintaining animal health without the excessive selection pressure on microorganisms [5, 38]. Therefore, more and more attention is paid to the programs of responsible application of antimicrobial drugs (antimicrobial stewardship), including biosecurity, vaccinations and dedicated diagnostics [44]. In parallel, there are developed the alternative prophylactic strategies: prebiotics, probiotics, phytobiotics, immune-stimulators, antimicrobial peptides and recombined vaccines [97]. Probiotic modulation of microbiome may reduce colonization by *Salmonella spp.* and *Campylobacter spp.* in poultry even by 70% [93] and immunomodulators such as ß-glucans increase non-specific resistance [106].

The effective veterinary prevention requires also inter-sectoral cooperation, consistent with the One Health approach. It includes cooperation of veterinarians, farmers, inspection services, scientists and administration in respect of the exchange of epidemiological data, harmonization of procedures, development of emergency plans and reporting the threats [122, 156, 66]. In the EU, there are the initiatives, integrating the veterinary supervision and public health, such as EU Animal Health Strategy or One Biosecurity Framework 944). Owing to this, it is possible to limit more effectively the diseases of zoonotic potential such as avian influenza, salmonellosis, leptospirosis or campylobacteriosis [39].

Social-economic and psychological factors affecting the implementation of biosecurity

Implementation of biosecurity in animal production farms is a multi-factor process, being dependent not only on availability of technology and infrastructure but also on the economic, social, organizational and psychological factors. In literature, it is emphasized that even the advanced technical measures remain ineffective if they are not approved and consequently applied by the farmers (34, 124). Human factors such as knowledge, approach, risk perception and motivation, have the crucial meaning in constructing the biosecurity systems [5, 165].

Economic problems are one of the most important barriers to the implementation of biological protection means. The investment costs covering modernization of infrastructure, building of sanitary zones, purchase of disinfectants, protective equipment and staff training are especially a significant burden to small and medium-sized farms [39, 66, 165]. The studies from Germany and Poland have revealed that the annual costs of biosecurity constitute 2.5–4.8 % of the value of gross production, with the dominating participation of expenses on sanitary agents [53, 165]. In big farms, the mentioned costs are compensated by the lower manufacturing losses and limitation of epizootics risk, whereas in family farms, the biosecurity is often perceived as economically loading problem [93]. The access to financial support instruments – donations such as ARiMR, EFSA Biosecurity Fund or PROW means 2021–2027, increases significantly the level of implementation, and lack of the stable programs lower the adaptation rate by 20–30% [39, 44]. Economic perception of the risk is equally significant: the farmers invest more eagerly in biosecurity when they perceive the diseases as a real economic threat. In the regions, covered with epizootic diseases such as ASF in the East Europe or HPAI in the West Europe, the level of investments is by a few times increased [38, 66]. Many producers do not perceive the direct economic profits and refer the biosecurity measures rather to public health protection than to their own production [128]. At the same time, numerous analyses confirm that biosecurity brings measurable economic profits, i.e. improvement of productivity, reduction of treatment costs and stabilization of production [37, 69].

Social factors including demographic structure of producers, the level of education, access to advisory assistance, and meaning of social networks [6, 132]. Younger farmers reveal more frequently the readiness to implement the innovations whereas the older people trust mainly in the experience [39]. The farms, functioning within the producer groups or cooperatives reach a higher level of compliance owing to the exchange of knowledge, logistic support and common audits [93, 165]. The decisions concerning the introduction of biological protection agents are often determined by the group influence – biosecurity acquires then a form of common good, the effectiveness of which is dependent on the collective observation of the principles [39]. In spite of the fact that many farmers declare that the biosecurity is important, the level of factual knowledge is often low: the studies show many gaps in understanding the mechanisms of disease transmissions and wrong convictions that the diseases are unavoidable element [83, 124].

Psychological factors include the perception of the risk, confidence in the institutions, feeling of own effectiveness and convictions concerning profitability of the undertaken measures [39, 97]. The farmers who had earlier experienced losses due to the infectious diseases are characterized by a greater motivation to implement the protective means [6]. A low perception of the risk leads to neglecting of threats and preferring the reactive approach i.e. introduction of the biosecurity principles as late as after occurrence of disease outbreak [5, 66]. A low level of confidence in the veterinary institutions is favourable for the resistance to the procedures, especially in the family farms [121, 156]. The so-called attitude-behaviour gap results, inter alia, from the lack of confidence to the effectiveness of the undertaken measures, cognitive conflicts or a low feeling of control [109]. The studies confirm the existence of the gap between the knowledge and practice; in spite of the awareness of the threats, biosecurity is often considered as expensive, time-consuming or low-effective activity [109]. The explanation of the mentioned discrepancy may be found by the psychological models, including the model of Aizen planned behaviour [2]. The effective behavioural interventions should strengthen the feeling of doership and control, instead of limiting to transfer of information about the threats. Training based upon the local cases which increase the identification with the problem and the readiness to change the behaviours may be a practical example [124].

The wrong convictions concerning biosecurity – overestimation of the role of the selected means (such as vaccination) with the simultaneous ignoring of critical elements such as quarantine or access control, are commonly recorded in the studies [83, 124]. In literature, the meaning of behavioural approaches and organizational psychology is growing up. Introduction of motivation systems, visual reminding (e.g. marking of the risk zones, information panels) and, also, intervention of "nudges" – scores, gamification, SMS reminding, improves the compliance with the procedures, even by 20–30% [79]. The results of the European studies indicate that the educational programs combined with the mechanisms of financial support increase the level of implementation by 35% in average as compared to the purely informational activities [39].

The studies show that the technical knowledge alone does not guarantee observing the recommendations; motivation, communication and relations between advisor and producer have a big meaning [120, 124]. Veterinary surgeon plays a role of advisor and facilitator of the change what requires combining epidemiological and communication competences. The effectiveness of transfer is increased when the advisor understands the context of the farm and adapts the recommendations to the real economic and organizational possibilities of the producer [115]. The models of co-creating where the biosecurity plans are developed together with the farmers are most effective [85, 126]. The effectiveness of the recommendations is significantly increased when the communication is based on the concrete, measurable profits such as improvement of production results, limitation of the health losses or lowering of the treatment costs [37]. The technologies such as motivation communication allow conquering the behavioural resistance and increase the compliance with the protocols, especially in the farms with a low degree of implementation [126].

Assessment of biosecurity effectiveness and evaluation instruments

The evaluation of the effectiveness of the biosecurity instruments enables verification of the implemented procedures and their constant improvement. The regular evaluation allows

to identify the weak points, assess the compliance with the legal regulations and analyze the impact of the prevention measures on the level of epizootic risk [38, 39]. The systematic evaluation supports the standardization of the practices and makes the adaptation of the proven solutions easier [66, 165]. The results of the studies conducted in 96 pig farms in Belgium and the Netherlands have revealed that the introduction of the periodical biosecurity audits lowered the risk of pathogens' transmission by 41% during two years [93] what stresses the meaning of the regular, documented evaluation.

The assessment of the biosecurity effectiveness requires application of the quality and quantity indicators. Most often, there is analyzed the frequency of incidence of infectious diseases, use of antibiotic, indicators of deaths and infringement of procedures [38, 39]. The evaluation includes also the number of biosecurity incidents, time of the response to detection of pathogen, degree of the staff training and the level of the compliance with the protocols. The high level of the compliance is correlated with the lower application of antibiotics and better production results what was indicated in the studies on the poultry and pig sectors [39, 66].

The economic indicators allow appreciating the relation of the costs of biosecurity measures and potential losses, resulting from the diseases. EFSA analyses indicate that the greatest participation in the risk reduction was recorded for control of transport (28%), equipment disinfection (21%) and training of the staff (18%) [49]. Environmental monitoring is also the meaningful element – it includes testing of the samples of water, air and feeds, enabling identification of the critical sites and verification of the efficacy of sanitary and disinfection procedures [93]. In practice, biosecurity monitoring is linked with the programs of the herd health control programs and limitation of the antibiotics use (38), facilitating the combination of the level of the compliance with the production and health results.

The basic instruments include questionnaires and control lists [39]. To evaluate the implementation, the biosecurity indices such as Biosecurity performance Index (BPI) are also employed; the mentioned indicators express, in scores, the level of compliance in the scale of 0–100 and consider the infrastructural as well as organizational elements [66]. The field audits, implemented by the veterinary service allow to determine the real situation in the farm and the degree of implementation of the biosecurity plan assumptions [53]. It is supplemented by the models of the risk analysis which facilitate the quantitative determination of the probability of introducing or disseminating pathogens, with the consideration of environmental and organizational conditions, and traffic of animals [106, 165].

The modern approach assumes integration of the evaluation of biosecurity and the quality and risk management systems such as ISO 9001, ISO 22000 or HACCP or One Biosecurity Framework [122, 156].

The mentioned integration allows combining the biological safety and supervision of the production, environmental and health processes, creating a coherent control system. The implementation of PDCA (Plan-Do-Check-Act) cycle supports constant improving of procedures and their updating in the varying epizootic conditions [38, 39]. The data from 120 dairy farms in the Netherlands and in Germany have indicated that the integration of biosecurity audits and HACCP system increased the compliance with the veterinary requirements by 29% during 18 months [165].

Implementation of the integrated systems brings practically the profits exceeding the reduction of the risk of diseases. The farms which employ the complex management of the resources demonstrate a lower consumption of chemical agents, energy and water and, simultaneously, they reach higher biosecurity effectiveness [97]. The comparability analyses from the Netherlands show that the farms, running the coordinated practices, obtain by 17%, averagely, higher BPI, in comparison to the farms deprived of the discussed type of the system [39]. The integrated early warning systems (EWS) employ the epidemiological, environmental, meteorological and commercial data to prognose the risk. The example may be the European ADIS system which collects the data from the EU member states and supports the coordination of the activities at the level of the EU [44].

Conclusions and recommendations for practice and policy of animal health

The effectiveness of biosecurity is dependent on the integration of technical, organizational and behavioural measures; the greatest differences in the implementation are found between the intensive and extensive management systems. The development of digital technologies, environmental monitoring, biosensors and automatization, increases significantly the possibilities of the early detection of threats; however, their effectiveness is determined by the technical resources and competences of the staff. In practice, the key problem is to strengthen the biosecurity culture via training, audits, modernization of infrastructure and development of field diagnostics, what facilitates the quick response and reduction of epizootic risk.

From the perspective of animal health policy, it is necessary to harmonize the biosecurity standards and implementation of the measures, supporting the small farms via the financial mechanisms and certification systems. Improvement of the data flow, integration of the national and the EU epidemiological databases and development of education compliant with the One Health conception are the foundation for the effective risk management and the response to crisis. The high level of confidence in veterinary institutions and the awareness of the economic consequences of epizootics remain the key factors of the approval of regulations and permanent rising of biological protection standards.

Literature

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