frontiers in Animal Science

TYPE Systematic Review
PUBLISHED 25 March 2026
DOI 10.3389/fanim.2026.1738787

OPEN ACCESS

EDITED BY
Elena Sorrentino,
University of Molise, Italy

REVIEWED BY
Lingjuan Wang-Li,
North Carolina State University,
United States
Marija Gogić,
Institute for Animal Husbandry, Serbia

*CORRESPONDENCE
Valentina Suprani
valentina.suprani4@unibo.it

RECEIVED 03 November 2025
REVISED 15 February 2026
ACCEPTED 18 February 2026
PUBLISHED 25 March 2026

CITATION
Suprani V, Agnusdei GP, Romanelli C, Aragrande M and Canali M (2026) The economic sustainability of biosecurity in pig farming: a systematic review with bibliometric, network and content analysis.
Front. Anim. Sci. 7:1738787.
doi: 10.3389/fanim.2026.1738787

The economic sustainability of biosecurity in pig farming: a systematic review with bibliometric, network and content analysis

Valentina Suprani [1]*, Giulio Paolo Agnusdei [2], Costanza Romanelli [1], Maurizio Aragrande [1] and Massimo Canali [1]

[1]Department of Agricultural and Food Sciences, University of Bologna, Bologna, Italy, [2]Department of Psychology and Health Sciences, Pegaso University, Napoli, Italy

As global pig production becomes increasingly intensive and consolidated, the economic and health risks associated with disease outbreaks in swine farming are rising. While biosecurity measures are recognized as essential for disease prevention and antimicrobial use reduction, their economic sustainability remains underexplored. This study aims to assess the current state of knowledge on the economic aspects of biosecurity in pig farming through a systematic literature review supported by bibliometric, network, and content analyses. A total of 586 scientific publications referring to economic aspects of biosecurity in pig farming, published from 1995 to 2023, were retrieved from Scopus, PubMed, and the Web of Science using PRISMA guidelines. Bibliometric analysis highlighted a growing academic interest in the topic, with an average annual growth rate of 13.89% and a notable publication peak in 2022. Network analysis identified four thematic clusters for the selected publications: swine health and virology, public health and food safety, animal disease management, and epidemiology. A more attentive focus on socio-economic issues related to biosecurity has emerged in recent years. To investigate more specifically the economic impacts, a content analysis was conducted on 25 studies reporting quantitative data on biosecurity costs. These studies were classified by supply chain phase, disease type, epidemiological design, and biosecurity measures. The majority focused on fattening farms and farrow-to-finish systems and examined internal biosecurity practices such as hygiene, disease management, and access control. While implementing biosecurity incurs upfront costs—particularly for infrastructure—these are often offset by reduced disease-related losses and increased productivity. However, cost-benefit ratios vary significantly by region, farm size, and disease prevalence. Findings indicate that, although economic evidence supports the long-term value of biosecurity, adoption remains limited, particularly among small-scale producers. This review underscores the need for more targeted and economically informed biosecurity strategies. Future research should prioritize cost-effectiveness analyses, policy tools to encourage adoption, and support mechanisms for vulnerable farms. A better understanding of the financial dimensions of biosecurity can help align health and economic sustainability goals in the swine sector.

KEYWORDS

biological risk management, disease prevention, swine production, financial impact, cost analysis

1 Introduction

Globally, the pig industry continues to follow a trend toward increased production and progressively larger and more concentrated operations, which amplify the economic and health risks associated with the potential spread of animal and zoonotic diseases. A substantial portion of the scientific literature has focused on analysing the epidemiology of pathologies such as PRRS, PED, and ASF, related with reducing productivity. Moreover, the growing need to strengthen disease prevention has prompted research into the effectiveness of biosecurity strategies in mitigating health risks on pig farms (Rowlands et al., 2008; Corzo et al., 2010; Stevenson et al., 2013; Zhou et al., 2018).

Farm biosecurity is a preventive action that refers to the combination of all the different measures (a set of management, protocols, practices, and physical measures) designed to reduce the risk of introduction, establishment and spread of disease agents to, from and within an animal population (Amass, 1999; Shortall et al., 2017; Saegerman et al., 2024).

There are two main components of farm biosecurity: external biosecurity and internal biosecurity. The former encompasses all the measures designed to prevent the introduction of infectious agents to uninfected farms and to limit the spread of diseases from already infected farms. Internal biosecurity, on the other hand, focuses on the strategies adopted to prevent the transmission of pathogens within the farm. Several studies have evaluated the effectiveness of key external and internal biosecurity measures. External risk factors may include distance from neighbouring farms (Christensen et al., 1990; Woeste and Grosse Beilage, 2007), animal transportation (Dee et al., 2004; Otake et al., 2010), people and vehicles as disease vectors (Amass et al., 2000), rodent control (Ospina-Pinto et al., 2017), quarantine protocols, and the use of semen (Fedorka-Cray et al., 1997; Woeste and Grosse Beilage, 2007). With respect to internal biosecurity, studies have examined the importance of farm management practices (Lurette et al., 2011; Isomura et al., 2018), cleaning and disinfection routines (Amass et al., 2000; Dione et al., 2018), farm workers' behaviours, vaccination programmes, and their collective impact on intensive pig farming (Layton et al., 2017).

The proper application of biosecurity measures plays a crucial role in keeping the risk of epidemics and the use of antimicrobials low (Laanen et al., 2013; Postma et al., 2016a; Collineau et al., 2017). These measures improve animal health, help combat antimicrobial resistance (AMR) (Rodrigues Da Costa et al., 2019; Alarcón et al., 2021), enhance overall technical performance (Laanen et al., 2013; Postma et al., 2016b), and increase farm profitability (Rojo-Gimeno et al., 2016).

For example, farms with higher levels of external biosecurity tend to have a positive correlation with increased piglet weaning rates, such as the number of piglets weaned per sow per year (Postma et al., 2016b). Furthermore, farms that maintain strong biosecurity practices also experience greater productivity, with a greater number of piglets born per sow per year and more fattening pigs sold annually (Dors et al., 2013).

Despite the enforcement of EU Regulation 2019/6, which sets strict guidelines on the use of antibiotics and other veterinary medicines in livestock production, including limitations on prophylactic and metaphylactic use of antibiotics, restrictions on critically important antibiotics, and a requirement for veterinary electronic prescriptions, many pig farmers continue to be hesitant to adopt effective biosecurity practices (Burton et al., 2008; Garforth et al., 2013), even in light of the well-documented and scientifically proven benefits of biosecurity practices for both animal health and farm profitability. Several key factors contribute to farmers' reluctance to adopt biosecurity measures, including economic, cultural, and practical considerations (Pao et al., 2022). Some may underestimate the risk of infectious diseases or believe that the likelihood of an outbreak is low, especially if they have not experienced significant health issues on their farms in the past (Garforth et al., 2013; Alarcón et al., 2021). Many farmers, accustomed to traditional methods and established routines, may not be motivated to follow biosecurity measures because they are seen as an intrusion into their established operations (Casal et al., 2007; Alarcón et al., 2021). This resistance to changing behavioural habits is common across many agricultural sectors and is often compounded by a lack of awareness of the long-term benefits of adopting new practices (Alarcón et al., 2021). In many instances, farmers may not fully understand how to implement biosecurity measures effectively or how these can be integrated into their operations without compromising productivity (Higgins et al., 2018). Limited training and support from experts or industry

Abbreviations: AMR, Antimicrobial resistance; AMU, Antimicrobial use; ASF, African swine fever; CSF, Classical swine fever; FMD, Foot and Mouth Disease; ID, Leveraging Keywords Plus; PCV2SI, Porcine Circovirus type 2 Subclinical Infection; PED, Porcine epidemic diarrhea; PEDV, Porcine epidemic diarrhea virus; PMWS, Postweaning multisystemic wasting syndrome; PRISMA, Preferred Reporting Items for Systematic reviews and Meta-Analyses; PRRS, Porcine reproductive and respiratory syndrome.

associations can create further barriers to adoption (Alarcón et al., 2021).

Additionally, some farmers are concerned that biosecurity measures involve complex, ongoing management and substantial costs in the long term. For example, maintaining infrastructure, managing supplies, and enforcing strict controls require continuous effort, which may not seem worthwhile without the promise of immediate financial returns. These requirements may also indirectly involve the hiring of additional staff to manage these tasks, although this is not always explicitly necessary. Pig farmers are also frequently under economic pressure, facing challenges such as fluctuating commodity prices, intense market competition, and narrow profit margins (Niemi et al., 2020). In this competitive environment, some may perceive biosecurity as an additional cost that offers no immediate, tangible benefits, particularly if their farms have not been impacted by major disease outbreaks (Fraser et al., 2010).

Furthermore, the lack of economic incentives or supportive agricultural policies that encourage the adoption of biosecurity measures adds another layer of resistance, hindering widespread implementation (Bâtie et al., 2023).

Different levels of biosecurity can be related to economic variables (Hennessy et al., 2005). The implementation of biosecurity often requires substantial investments in infrastructure, such as fencing, disinfection stations, quarantine systems, and equipment, to control vehicle access and entry points.

Several studies indicate that biosecurity measures can lead to higher profits (Fasina et al., 2012), but this implies additional farm investments, which may not always bring immediate gains to farmers (Niemi et al., 2016).

A conceptual framework on the impacts of African swine fever (ASF) in Timor-Leste (Berends et al., 2021) proposes two alternative economic scenarios for farms in high-risk areas. In the first scenario, preventive biosecurity measures are not adopted. This leads to reduced farm productivity and revenues, coupled with increased costs for animal treatments. As a result, farms experience profit losses, which drive investment contraction and further reductions in productivity, creating a self-reinforcing negative loop. In the second scenario, preventive biosecurity measures are implemented. These measures help reduce mortality, morbidity, and productivity losses. While their adoption increases farm costs, the expenses for treating sick animals decrease, and revenues remain stable. Consequently, profit losses are mitigated, allowing continued investment in breeding and further biosecurity improvements. From this perspective, the application of correct biosecurity practices not only safeguards farms' animals and productive assets but also becomes a cornerstone for economic stability and success.

While numerous studies have examined the costs and benefits of specific eradication and containment programs for swine diseases (Thompson and Tebbens, 2007; Hauser and McCarthy, 2009; Gohin and Rault, 2013), analyses of the economic aspects of biosecurity in intensive pig farming still appear to be relatively unexplored. This highlights the need for a deeper understanding of how to optimize expenditures in the selection of cost-effective biosecurity measures (Kompas et al., 2015).

The aim of this paper is to review the current state of the art and present findings from bibliometric, network and content analyses focusing on the economic aspects of biosecurity in swine farming. Specifically, the study addresses the following research questions:

RQ_1: Is the economic sustainability of biosecurity an emerging trend in the field of the swine supply chain?

RQ_2: How does economic sustainability influence biosecurity practices in pig farming?

RQ_3: What are the economic aspects and cost analyses of biosecurity measures in pig farming discussed in the scientific literature?

2 Materials and methods

A systematic literature review was conducted to summarize studies in the research area, with the support of bibliometric, network and content analyses to address the research questions (Fahimnia et al., 2015; Qaiser et al., 2017). As emphasized by Maditati et al. (2018) and Zupic and Čater (2015), systematic reviews must adhere to transparent and replicable methodologies to ensure reliability and minimize the subjective biases that are often present in literature reviews. To answer RQ1, bibliometric analysis, a technique that applies quantitative methods to map and assess research topics, publication trends, and leading journals, was employed. The analyses were performed via the bibliometric R tool, an R package, to generate comprehensive bibliometric results (Aria and Cuccurullo, 2017). For RQ2, the study utilizes network analysis, leveraging Keywords Plus (ID) from the Scopus index for co-occurrence analysis and VOS viewer 1.6.14 software to explore research themes, keyword patterns, and clusters. The content analysis was performed on a selected sample of papers to address RQ3. A classification framework was developed to summarize and identify the main themes in the literature, as well as to highlight gaps in research (Agnusdei and Coluccia, 2022).

2.1 Data collection

In this study, the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) methodology and guidelines were applied to select relevant papers through a systematic process of identification, screening, eligibility and inclusion evaluation (Agnusdei and Coluccia, 2022). The articles included in the review were published between 1995 and 2023. Document extraction was conducted via Scopus, PubMed, and ISI Web of Knowledge, and the data were subsequently collected in Excel.

During the identification phase, three distinct groups of keywords were used. Group A encompasses keywords related to animal species, Group B includes keywords from the economic research field, and Group C consists of biosecurity-related terms (Table 1). The three groups of keywords were combined via the Boolean operator "AND", whereas within each group, the keywords were linked via the Boolean operator "OR" to account for variations and synonyms within each category.

The database query was conducted on November 22, 2023. Documents were filtered on the basis of subject area, language, and

TABLE 1 Identification and grouping of keywords.

Group A animal species	Group B economic terms	Group C biosecurity
pig swine porcine	economic loss impact cost benefit budget investment management	biosecurity bio-check

source type, following the search protocol outlined in Table 2. The extracted data included citation details (e.g., authors, document titles, affiliations, publication years, and citation counts), abstracts and indexed keywords. Duplicate documents, those with incomplete information, or those deemed irrelevant to the topic were excluded from the final dataset.

A total of 586 documents were ultimately selected for the study. All these documents were included in the sample for the bibliometric and network analyses, while a separate selection process was conducted for the content analysis. Three authors independently and thoroughly reviewed all the documents to avoid reading bias and selected the articles that were considered eligible for inclusion in the content analysis. After a critical appraisal of the selected articles, an agreement was reached among all the authors regarding the inclusion/exclusion of the papers (for the inclusion/exclusion criteria, see the next subsection). As a result, 25 studies were identified as directly related to the economic aspects and cost analyses of biosecurity in the swine supply chain and were considered for content analysis (Figure 1).

2.2 Bibliometric, network and content analyses

To conduct the bibliometric analysis, documents obtained from Scopus in.csv format were imported into R software and transformed into a bibliographic data frame. The analysis included assessing annual scientific production, annual percentage growth, average citations per year, document types, most prolific authors, prominent journals, and top countries for citations and document counts. The network analysis was performed by using VOS viewer 1.6.14 software. For this purpose, the most relevant index keywords were identified to define the documents associated with a topic. The network analysis consists of a keyword co-occurrence analysis that graphically shows the link between each keyword. Specifically, the full counting method, which assigns equal weights to each co-occurrence, was used to conduct the co-occurrence analysis of the index keywords. The number of documents in which two index keywords occur together was used to determine the relatedness of the keywords.

TABLE 2 Search protocols for databases.

Subject area	Language	Source types
Veterinary Agricultural and Biological Sciences Immunology and Microbiology Medicine Biochemistry, Genetics and Molecular Biology Multidisciplinary Environmental Science Social Sciences Engineering Chemical Engineering Pharmacology, Toxicology and Pharmaceutics Economics, Econometrics and Finance Earth and Planetary Sciences Business, Management and Accounting	English	Journals

A total of 13,548 index keywords were chosen, and off-topic keywords were eliminated. Keywords with at least 10 occurrences were included. The network visualization of 192 keywords extracted showed the weight of the keywords as represented by the circle's dimension, the relationship between two words as shown by the lines (thicker lines indicate stronger word connections), and the research clusters to which the index keywords belong as indicated by the various colours (Waltman et al., 2010). In accordance with van Eck and Waltman, 2009, and Waltman et al., 2010, the layout was constructed by normalizing the strength of the links between the elements via the association strength method.

For the content analysis, four criteria were identified to classify the documents to investigate the economic sustainability of biosecurity in the swine supply chain: (i) supply chain phase, (ii) disease, (iii) epidemiological study types, and (iv) economic impact of biosecurity. Each document was reviewed and classified according to the four abovementioned criteria.

On the basis of the supply chain phase criterion, the selected documents were attributed to the following categories:

- Farrow-to-finish refers to studies that consider biosecurity aspects in the entire life cycle of swine production, from breeding and farrowing to finishing and market readiness.
- Farrow-to-wean refers to studies focusing on biosecurity measures during the breeding and farrowing stages, where piglets are produced, weaned, and subsequently sold to other producers for further growth and finishing.
- finisher, referring to studies that consider biosecurity aspects from the postweaning stage to final market weight, optimizing swine growth and health for meat production.

The disease criterion pertains to the swine illness examined in the selected studies. This classification criterion is relevant because the economic aspects of biosecurity may vary depending on the diseases that require different measures for prevention and management. The identified diseases are as follows:

- African swine fever (ASF).
- Antimicrobial use (AMU) – antimicrobial resistance (AMR).
- Campylobacter infection.
- Classical rabies.
- Classical swine fever (CSF).
- General animal health status.
- Porcine epidemic diarrhea virus (PEDV).
- Porcine reproductive and respiratory syndrome (PRRS).

10.3389/fanim.2026.1738787

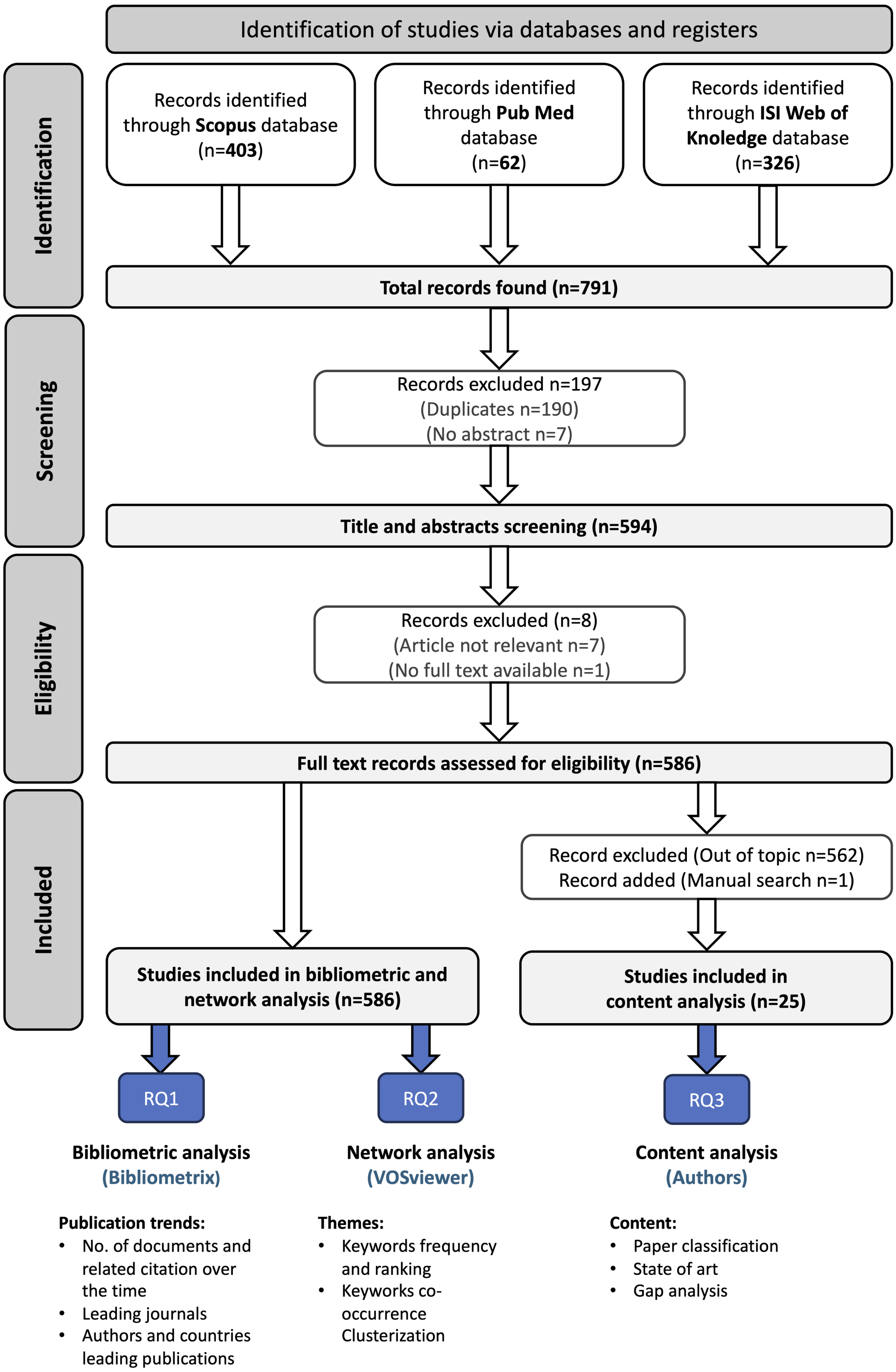

FIGURE 1
Selection of studies to be included in the systematic review.

- Foot and Mouth Disease (FMD).
- Postweaning multisystemic wasting syndrome (PMWS).
- Porcine Circovirus type 2 Subclinical Infection (PCV2SI).
- Salmonella.
- Toxoplasmosis.

The documents were also organized according to the epidemiological study types:

- case–control studies that investigate associations between individuals with a specific condition (cases) and those without it (controls) by analysing past exposures, which are often used for rare diseases;

- cross-sectional studies that collect data at a single point in time to provide a snapshot of a population, evaluate the prevalence of a condition or exposure and identify correlations between variables;
- case studies that analyse individual cases, groups, or situations, offering detailed information to gain comprehensive insights;
- modelling and simulation studies that use mathematical, statistical, or computational models to simulate complex phenomena and predict outcomes on the basis of different variables;
- reviews that make systematic evaluations of existing research on a specific topic, summarizing evidence and identifying gaps or new directions;
- surveys as a tool for gathering data through direct questions to a sample population, aimed at understanding opinions, behaviours, or trends within a given group.

3 Results

3.1 Bibliometric analysis

Figure 2 shows the annual scientific production in the field, and considerable growth in published documents has emerged, especially over the last 5 years. Table 3 reports the main bibliometric results. The results show that the economic aspects of biosecurity in the swine supply chain are gaining importance and that there is a growing interest among researchers and practitioners. The extracted and analysed sample consisted of 586 documents. A total of 2679 authors contributed to the publication of the documents in 193 different journals. The average citation level per document is equal to 20.75, and the average annual publication growth rate is equal to 13.89% for the years from 1995 to 2023. The first study within the research field was published in 1995, and in the following years, until 2007, the number of published documents was very low, with a maximum of 4 documents per year. There was a constant increase in the number of published documents from 2008 to 2019. In 2022, a peak was registered, with 99 published documents and an increase of 55% compared with the previous year. Additionally, for 2023, the interest trend in the field was confirmed.

The top ten leading journals in terms of published documents are shown in Table 4. All the listed journals focus on veterinary medicine- and animal health-related topics. Preventive Veterinary Medicine is the journal in which the most documents are published (83), followed by Frontiers in Veterinary Medicine (Aria and Cuccurullo, 2017) and Transboundary and Emerging Diseases (Berends et al., 2021). The abovementioned journals focus on animal disease prevention strategies and explore interspecies transmission risks. Porcine Health Management (Pao et al., 2022) specializes in porcine health. There are no journals specializing in the economic aspects of animal biosecurity, which reflects the lack of journals specializing in animal health economics. The JCR impact factor (IF) (referred to as year 2022) never exceeds 4.5; however, many journals are positioned in the first quartile (Q1), highlighting their relevance.

Table 5 presents the top seven authors with the highest document output (at least 10 published documents) in the analysed research field, along with their productivity assessed by the H index. The H-index, an author-level metric, gauges both the productivity and citation impact of publications by considering the ordered list of the researcher's most cited papers and the number of citations received in other works (Garousi and Fernandes, 2017; Simoes and Crespo, 2020).

In Table 6, the most productive countries in terms of selected published documents are listed. The authors affiliated with United States universities represent an outlier, with 106 selected documents. Australia, the United Kingdom and Belgium then register a relevant number of published documents. Table 6 also

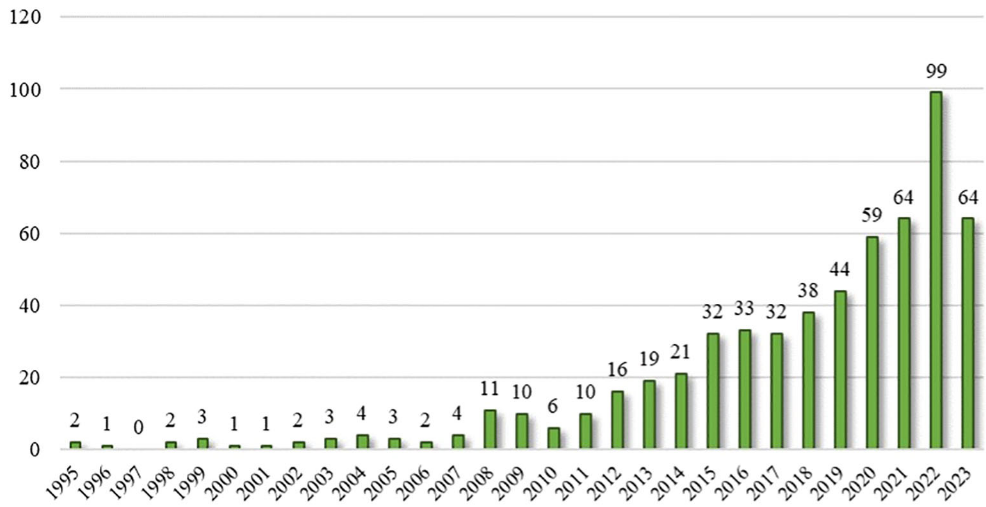

FIGURE 2
Annual trend in the number of publications.

TABLE 3 Main results of bibliometric analysis.

Main information data	Values
Documents	586
Sources (Journals)	193
Keywords Plus (ID)	3,548
Author's keywords (DE)	1,511
Timespan	1995 - 2023
Average citations per document	20.75
Authors	2,679
Author appearances	3,609
Documents per author	0.223
Co-Authors per document	6.04
International coauthorship	34.95%
Annual percentual growth rate	13.89%

provides information on the number of published documents authored exclusively by individuals from a single country (Single Country Publications) or by authors from different countries (Multiple Country Publications). Sweden is the country with the highest percentage of intercountry collaboration (60%), followed by Belgium (43.4%).

3.2 Network analysis

A comprehensive analysis was conducted on a total of 192 keywords extracted from the documents. The frequency of index keywords was tallied to generate a ranking, and the results are presented in Table 7. Among the top ten keywords, "Animal" emerged as the most recurrent keyword, appearing 327 times. Notably, several keywords in this ranking are associated with swine, such as "Pig," "Swine," "Swine disease," "African swine fever," and "Pig farming." This underscores the importance of the context related to the transmission of diseases within the pig sector.

Figure 3 depicts a network visualization showing the co-occurrence of keywords between 1995 and 2023. The analysis considered keywords that appeared together in a minimum of ten documents. The closeness and thickness of the lines connecting two keywords convey the frequency of their co-occurrence, whereas the size of a node reflects the frequency of its occurrence as a keyword (Strozzi et al., 2017; Donthu et al., 2021). The network analysis revealed four clusters of connected topics: swine health and virology (red cluster), public health and food safety (green cluster), animal disease management (blue cluster), and epidemiology and disease studies (yellow cluster).

The red cluster, named "swine health and virology" (60 items), refers to studies focused on veterinary virology and swine health. The keywords in this cluster refer to various aspects, including virus identification, diagnosis, genetics, immunology, and swine diseases. "Virus detection", "virology", "virus infection", and "virus transmission" indicate the centrality of viruses in the research field. The green cluster, named "biosecurity and socioeconomic impact in swine farming" (55 items), refers to studies that emphasize the role of biosecurity in safeguarding food safety and preventing contamination in swine products. The presence of "socioeconomics" and "agricultural workers" highlights the economic and social aspects of swine farming, suggesting an interdependence between disease management, biosecurity, and the economic well-being of farmers and industry operators. The blue cluster, named "animal disease management" (52 items), refers to studies concerning management aspects of animal diseases. Keywords such as "Suidae," "animal husbandry," "infection control," "disease outbreaks," and "attitude to health" indicate connections among swine disease management, infection control, and operators' approaches to animal health.

The yellow cluster is named "epidemiology and disease studies" (25 items) and refers to keywords focused on the epidemiology of animal diseases, with particular attention given to infections such as "Salmonella" and "Saline disease". The keywords in this cluster focus on understanding the spread of swine diseases, identifying risk factors, and analysing prevalence through epidemiological and diagnostic approaches. This information is crucial for evaluating the economic impact of biosecurity in pig farming, as it directly influences livestock health and pork production.

In general, each cluster seems to be focused on a specific aspect of animal health, from scientific research and virology to disease management, agricultural administration, and epidemiology. The overlay visualization of keyword co-occurrence in Figure 4 reveals a

TABLE 4 Leading journals by number of selected published documents.

Journal	Publisher	No. of documents	Quartile	Impact factor (2022)
Preventive Veterinary Medicine	Elsevier	83	Q1	2.6
Frontiers in Veterinary Science	Frontiers	43	Q1	3.2
Transboundary and Emerging Diseases	Wiley	36	Q1	4.5
Porcine Health Management	Springer	26	Q1	3.6
Animals	MDPI	18	Q1	3.0
Plos One	PLOS	15	Q1	–
Pathogens	MDPI	13	Q2	3.7
BMC Veterinary Research	Springer	12	Q1	2.9
Veterinary Microbiology	Elsevier	11	Q1	3.3
Journal of Swine Health and Production	AASV	10	Q3	–

TABLE 5 Leading authors by number of selected published documents.

Author	Affiliation	Publications on the topic	H-index
Dewulf J.	Universiteit Gent (Belgium)	24	62
Maes D.	Universiteit Gent (Belgium)	14	54
Postma M.	Universiteit Gent (Belgium)	13	20
Chenais E.	Statens Veterinärmedicinska anstalt (Sweden)	10	16
Poljak Z.	Ontario Veterinary College (Canada)	10	24
Sjölund M.	Statens Veterinärmedicinska anstalt (Sweden)	10	17
Stärk K.D.C.	Royal Veterinary College University of London (United Kingdom)	10	44

high concentration of published documents in the last five years. Furthermore, animal biosecurity has emerged as a key issue because of the heightened awareness of health, environmental, and economic risks associated with animal diseases, especially in the context of increasing globalization and interconnections between economies.

3.3 Content analysis

A total of 25 papers were selected for the content analysis, and a classification system was developed to summarize and identify key themes in the literature. These papers were chosen for their presentation of quantitative data on the economic aspects and cost analyses of biosecurity. The papers were grouped on the basis of supply chain segment, study design, disease type, biosecurity structural measures and procedures, and geographical region. These groups have been adopted to divide the results into the following subsections and present them in a way that reflects the relevant characteristics of the research field and highlights the contributions of the economic aspects of biosecurity. For the supply chain classification (Table 8), three categories emerged: farrow-to-finish, farrow-to-weaning, and finisher. Among the selected papers, 78% focused on the farrow-to-finish category, 13% on farrow-to-weaning, and 9% on finisher operations.

The higher percentage of studies on farrow-to-finish operations reflects the fact that farms covering all stages of pig growth are more common. In terms of disease focus, Table 9 illustrates the classification of studies that dealt with the economics and costs of biosecurity measures according to the type of disease found on the farm during data collection. In one article, it was possible to observe the presence of more than one disease in the herd. The 22% of papers addressed ASF, followed by PRRS (15%), general animal health (15%), CSF (11%), PEDV (11%), and Salmonella and Campylobacter infections (7%). Only 4% of the papers focused on AMR, FMD, toxoplasmosis, PCV2SI, and postweekly multisystemic wasting syndrome. These data can be attributed to the fact that since the trend of publications has been increasing for several decades, ASF and PRRS, which are the most recently spread viral diseases in pig farms, have been studied.

With respect to study design, 33% of the papers employed a cross-sectional approach, 29% conducted case studies, 21% used modelling and simulation, and 8% applied a case–control design. Review and survey papers each represented 4% of the sample (Table 10).

The papers examining the economics and costs of biosecurity measures (Table 11) have focused primarily on those associated with internal biosecurity procedures, accounting for 60% of the studies. These costs were followed by the costs of external biosecurity procedures (33%), the costs of structural measures for internal biosecurity (5%) and the costs of structural measures for external biosecurity (2%). Studies that address structural biosecurity measures have analysed the costs related to fences (external biosecurity), water access and control, and air filtration systems (internal biosecurity).

The procedures with reported cost data were further subcategorized, revealing a total of 42 measures across different procedure subcategories (Table 12). Disease management presented the highest number of measures per subcategory (Amass et al., 2000), followed by smaller, more uniform numbers in other categories.

As shown in Table 13, the number of studies addressing each procedure subcategory varied. Disease management was covered in 15 studies, followed by hygiene control (12 studies) and access to and control by workers and visitors (12 studies). Other frequently

TABLE 6 Top 10 most productive countries by number of selected published documents.

Country	No. documents	Single country publication (SCP)	Multiple country publications (MCP)	MCP ratio
United States	106	73	33	33.1%
Australia	31	21	10	32.3%
United Kingdom	31	19	12	38.7%
Belgium	30	17	13	43.4%
China	25	21	4	16.0%
Italy	24	17	7	29.2%
Canada	21	17	4	19.0%
France	21	16	5	23.8%
Sweden	20	8	12	60.0%
Spain	17	12	5	29.4%

TABLE 7 Top 10 most frequent index keywords in the selected published documents.

Articles keywords-plus (ID)	Articles
Animal	327
Pig	306
Swine	293
Swine disease	186
Animal husbandry	159
Biosecurity	140
African Swine Fever	126
Risk factor	125
Epidemic	107
Pig farming	89

analysed measures included control of transport vehicles (8 studies), management of cadavers (7 studies), and handling sick animals (7 studies), with fewer studies on other biosecurity procedures. The higher frequency of cost analyses for disease management, hygiene control, access control for workers and visitors, and transport vehicle controls suggests that these procedures are considered particularly critical in biosecurity. Access control for workers and visitors, along with transport vehicle controls, are biosecurity measures that pose a significant risk of introducing contamination from external sources. Moreover, disease management and hygiene control are essential for preventing the spread of disease within farms.

Finally, the papers were categorized by region: 63% of the studies were conducted in Europe, 16% in the Americas, 11% in Asia, and 10% in Africa (Table 14).

On the basis of general industry knowledge and the available literature, we can make some general observations about the potential costs and benefits of biosecurity. In Europe, biosecurity measures, while essential, can increase operational costs; however, these expenses are often lower than the potential losses from outbreaks such as ASF. Studies across Europe illustrate the diverse costs associated with biosecurity implementation. In the Netherlands, enhanced biosecurity for toxoplasmosis prevention in pig farming can increase costs by €1.1 million to €2.5 million for the whole country (Suijkerbuijk et al., 2019), whereas in Spain, biosecurity on outdoor pig farms with an average number of 501 pigs per farm incurs approximately €14,780 per farm (Jiménez-Ruiz et al., 2022). In Belgium, a cost-accounting analysis revealed a median increase of €3.96 per sow annually for tailored biosecurity advice, yet improvements in internal biosecurity often led to only modest cost increases (Rojo-Gimeno et al., 2016). For example, a German study reported a mere 2% increase in total costs per farm with improved internal biosecurity and management practices (Nathues et al., 2018). In the United Kingdom, instituting a visitor policy incurs minimal costs, although the construction of isolation hospital pens can be significant, estimated at €157.96 (1 £ = 1,19 €) per pig space in 2012 (Alarcón et al., 2021). The Danish finisher pig industry experiences considerable costs from mandatory faecal sampling, totaling approximately €1.5 million, whereas the cost of each round for the farmer is only 350–470 € (Baptista et al., 2009). Conversely, the economic costs of disease outbreaks can be far greater. For example, the ASF outbreak in Romania led to direct costs estimated at €502,967,500 (Ladoşi et al., 2023), and a single ASF outbreak in Bulgaria can result in economic losses of approximately €230,000 (1 BGN = 0.51€) (Ivanova and Ivanova, 2019). In Serbia, compensation costs for an ASF-affected sow or boar are €350, whereas control measures on a 2,000-square-

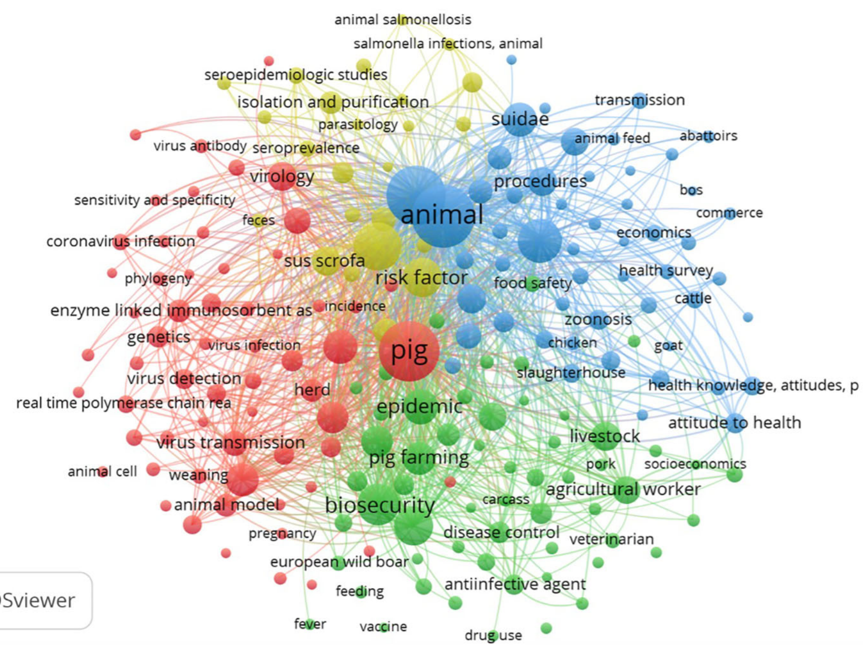

FIGURE 3
Network visualization of keyword co-occurrence analysis.

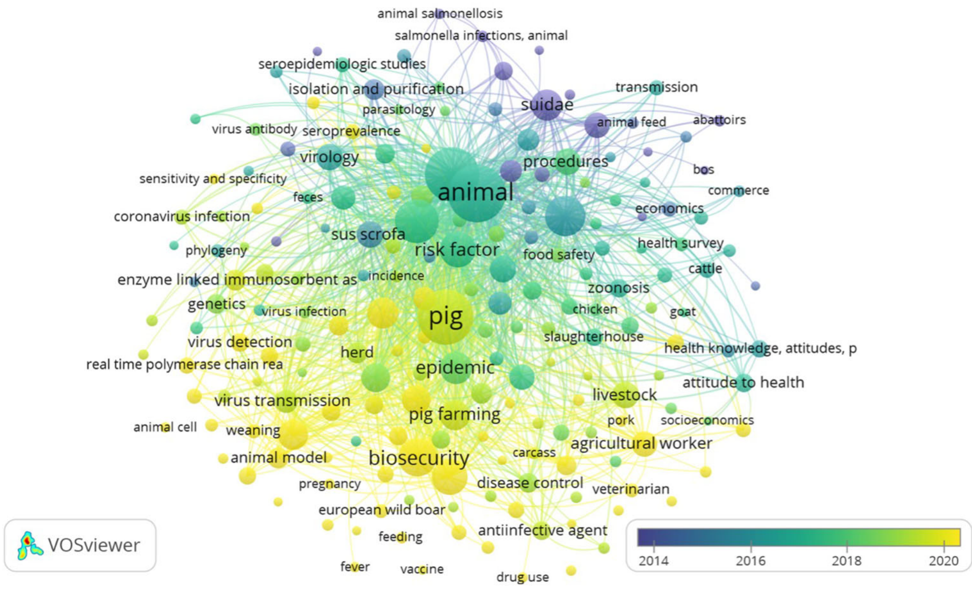

FIGURE 4
Overlay visualization of keyword co-occurrence analysis.

meter farm with five fatteners can cost approximately €1,000 (Polaček et al., 2021). Evaluations of four disease outbreak scenarios in Serbia revealed associated costs for cleaning, disinfection, euthanasia, compensation, carcass disposal, vaccination, and surveillance ranging from €143,430 to €367,110 (Stanojevic et al., 2015). Belgium's experience underscores how biosecurity improvements can positively impact both economic and health outcomes. In a cost-accounting analysis, an increase of €3.96 per sow per year in biosecurity costs from tailored advice was offset by a €2.68 reduction in antibiotic costs and by an increase of €39.21 in enterprise profit per sow per year. This demonstrates how reducing antibiotic usage and enhancing herd management can yield both cost savings and profitability (Rojo-Gimeno et al., 2016).

The analysis of papers from the Americas underscores the substantial economic impact of PEDV on the swine industry. Implementing air filtration systems, an effective preventative measure against PEDV and other respiratory diseases, can be costly, averaging $150 to $200 per sow (or $450,000 to $600,000 for a 3,000-sow herd) (Alonso et al., 2013). However, the potential losses from a single PEDV outbreak are often far more severe. For example, in Mexico, a PEDV outbreak can lead to significant losses, primarily due to piglet mortality and reproductive challenges, with eradication costs potentially exceeding $800,000 per herd (Garrido-Mantilla et al., 2022). Similarly, in Canada, an outbreak can result in annual losses of approximately $300000 for a 700-sow farm. Strategic biosecurity interventions, such as front-loading gilts with infected material, have been shown to significantly reduce these financial losses (Weng et al., 2016).

In Asia, the swine industry faces substantial economic challenges from diseases such as PRRSV, FMD, and PEDV. In Cambodia, a PRRS outbreak can lead to annual losses averaging $425.14 per smallholder farmer ($494.33, $387.61, and $393.48 per year for a two-sow breeder, a five-pig fattener, and a single-sow, three-pig farrow-to-finish/breeder, respectively) (Zhang et al., 2017). However, the authors reported that adopting both biosecurity and vaccination strategies was 100% effective against the risk of infection with PRRS and provided total prevention of weight loss and death. Vietnam provides further insight into the impact of disease on various farm sizes. Large-scale farms experience the highest losses due to PRRS, with a 41% reduction

TABLE 8 Classification of papers based on supply chains.

Supply chain	% of papers
Farrow-to-finish	78%
Farrow to weaning	13%
Finisher	9%
Total	100%

TABLE 9 Classification of papers based on disease.

Disease	No. of papers
African swine fever	6
Antimicrobial use and resistance	1
Classical rabies	1
Classical swine fever	3
Foot-and-mouth disease	2
General animal health status	4
Porcine epidemic diarrhea virus	3
Porcine reproductive and respiratory syndrome	4
Postweaning multisystemic wasting syndrome	1
Porcine Circovirus type 2	1
Salmonella	2
Campylobacter infection	1
Toxoplasmosis	1

TABLE 10 Classification of papers by study type.

Study type	% of papers
Cross sectional	33%
Case study	29%
Modelling and simulation	21%
Case control	8%
Review	4%
Survay	4%
Total	100%

in the gross margin (approximately $18,846). Fattening farms incur a 38% loss ($7,014), whereas smallholder farms face the most significant proportional loss, at 63% of their gross margin ($2,350). The average total cost of PRRS was estimated at $7,722, $2,673, and $1,470 for large farms, fattening farms, and smallholders, respectively (Pham et al., 2017).

In Africa, implementing robust biosecurity measures is essential to protect the swine industry from devastating diseases such as ASF. In Uganda, farmers need to invest only $0.72 (1 Ug Shs = 0,00027 US$) per week per grower to establish basic biosecurity practices (Ouma et al., 2018). In Nigeria, the annual cost of comprehensive biosecurity measures can reach $9,232.62 per farm (a 122-sow farrow-to-finish pig farm). However, the benefits significantly outweigh these costs, as preventing a single ASF outbreak can save farmers up to $910,836 annually (Fasina et al., 2012).

4 Discussion and conclusions

Studies specifically investigating the economic implications of enhancing biosecurity in animal production remain relatively rare. However, the number of publications on farm biosecurity that mention its economic implications has increased significantly, particularly over the last five years of the analysis. From 1995-2023, the average annual growth rate of publications responding to the selection criteria for the bibliographic and network analysis was 13.89%, with a notable peak in 2022, when 99 papers were published – representing a 55% increase compared with the previous year. The 2023 data show a decline, likely due to partial data collection, as the extraction was conducted in November and did not account for the full year. This increase of the focus on the economic implications of biosecurity may indicate a raising awareness among researchers and scientists about demonstrating that biosecurity not only protects animal health but can also yield significant economic benefits to farmers. Indeed, these analyses provide valuable insights for farmers, researchers, and policymakers, emphasizing the critical intersection between scientific research, agricultural practices, and the regulatory framework. The analysis also reveals considerable regional heterogeneity in biosecurity expenditures, reflecting differences in production systems, regulatory frameworks, and technological intensity.

The economic aspects and cost analyses of biosecurity measures in pig farming, as discussed in the analysis of 25 selected papers, highlight several key findings. The farrow-to-finish farm category has been the most studied, suggesting that farmers in this category prioritize controlling the entire production process for cost

TABLE 11 Studies have focused on structural measures and procedures.

Biosecurity measures	Procedures/structural measures	% of papers
Internal biosecurity	Procedures	60%
	Structural measures	5%
External biosecurity	Procedures	33%
	Structural measures	2%
Total		100%

TABLE 12 Number of measures per procedure subcategory.

Subcategories	No. of measures
Waste management	1
Measures to prevent contact with wild animals and pest	1
Dedicated equipment	2
Management of external areas	1
Purchasing policy	2
Control of feed and water	4
Management of cadavers	4
Handling sick animals	2
Cleaning and disinfection protocols	2
Control of transport vehicles	4
Access and control of workers and visitors	5
Disease management	12
Hygiene control	2
Total	42

TABLE 13 Number of papers per procedure subcategory.

Subcategories	No. of papers
Waste management	2
Measures to prevent contact with wild animals and pest	3
Dedicated equipment	4
Management of external areas	2
Purchasing policy	5
Control of feed and water	6
Management of cadavers	7
Handling sick animals	7
Cleaning and disinfection protocols	2
Control of transport vehicles	8
Access and control of workers and visitors	12
Disease management	15
Hygiene control	12
Total	85

TABLE 14 Classification of the papers by geographical region.

Geographical regions	% of papers
Europe	63%
America	16%
Asia	11%
Africa	10%
Total	100%

optimization through economies of scale. The conclusions drawn from the analysis of the economic impact of disease outbreaks on the swine industry clearly indicate that although biosecurity measures can lead to higher operational costs, their long-term benefits often far outweigh these expenses – both in terms of preventing disease outbreaks and increasing profitability – and disease prevention they offer, make them a sound financial strategy for safeguarding the swine industry. Indeed, disease outbreaks can lead to significant economic losses, often far exceeding the costs of implementing biosecurity measures. Furthermore, key prevention measures – such as disease management, hygiene protocols and access control – are critical for ensuring both economic and health outcomes in pig farming operations. From a business management perspective, the focus of cost analyses on these aspects reflects their direct impact on daily operational decisions. However, limited or inadequate on-farm infrastructure for the rational and effective implementation of biosecurity measures – most commonly observed in small-scale farms, backyard or household operations, farms run by elderly farmers, or those equipped with obsolete facilities – can in itself represent a significant constraint, including in terms of controlling biosecurity management costs, thereby limiting their adoption. Consequently, limited capital availability and a low propensity to invest also end up affecting both biosecurity costs and the overall health status of pig farms.

The economic impact of disease outbreaks on the swine industry is substantial, with costs varying across regions and disease types. For example, ASF outbreaks in Europe have been shown to cause millions of euros in losses, far greater than the biosecurity costs required to prevent such outbreaks. Measures such as hygiene protocols, disease management, and access control for workers and visitors were highlighted as key cost drivers. These procedures are essential for preventing disease spread within farms and limiting external contamination and are therefore considered as critical components of external biosecurity. Unfortunately, owing to the limited data available in the analysed papers, it was not possible to conduct a comprehensive analysis of the specific costs and losses associated with biosecurity measures and disease outbreaks in each region. However, the area with the highest biosecurity costs seems to be Europe, particularly in countries such as the Netherlands and Belgium, which require significant investments to adopt preventive measures. In the Netherlands, for example, improving biosecurity practices can lead to cost increases ranging from €1.1 million to €2.5 million, mainly to prevent devastating outbreaks such as ASF. In general, while Europe has the highest biosecurity costs, the North American region (particularly Canada and the United States) closely follows, with costs related to the installation of air filtration systems, which, although expensive, help reduce economic losses from diseases such as PEDV. These findings suggest that biosecurity-related expenditures on pig farms are driven by the combined effects of technological intensity and regulatory stringency. Higher costs are typically observed in advanced and intensive production systems, where significant investments are required to reduce the risk of major economic losses from disease spread, particularly in areas with a high concentration of large-scale operations. Regulatory frameworks further shape these expenditures, especially in countries with stricter animal health, welfare, and environmental standards. As a result, regions such as Europe and North America exhibit higher biosecurity costs than other major producing areas operating under less restrictive regulatory conditions.

Differences in biosecurity costs and adoption across regions also have implications for international trade. Regions with stricter biosecurity standards, such as Europe and North America, may face a competitive disadvantage due to higher production costs. This disadvantage can be offset by improved disease control, lower frequency of outbreaks, and better market access. By contrast, regions where biosecurity investments are more limited may achieve immediate cost advantages but remain more vulnerable to trade disruptions caused by epidemics and export bans. However, when pandemic-type diseases spread from high-production areas with low biosecurity – against which available therapies are largely ineffective and stringent biosecurity measures do not always succeed in limiting the transmission of infections, as in the case of ASF – producers in countries adhering to the highest standards also incur substantial losses.

In this context, findings suggest that strengthening biosecurity requires also an integrated policy approach. First, biosecurity policies should integrate economic incentives and structural support measures to promote the adoption of more sustainable and safe farming practices. A key priority must be the allocation of adequate resources, to support the implementation of good health management practices and structural upgrading of farms. It means that farm support should be aimed not only at improving daily practices but also at developing modern and safe infrastructure to facilitate the implementation of biosecurity measures. Another useful strategy could be strengthening incentives for the upgrading of existing farm facilities, with particular attention to those that requiring structural interventions to comply with health and safety standards. Early retirement incentives could also serve as a support measure to encourage generational renewal in farms, facilitating a transition to more modern and effective farm practices. Moreover, the improvement of biosecurity should not focus solely on upgrading physical structures but also on the adoption of modern management practices, digitization, and advanced disease monitoring systems. For these changes to occur, significant political incentives will be necessary, such as funding for restructuring, tax breaks, and increased training to support farmers in adopting innovative technologies and practices. Additionally, it would be essential to encourage investment in the renewal of structures and the introduction of new technologies that can enhance biosecurity. Rural development policies could finance such investments, supporting not only farmers but also other supply chain operators, with the goal of promoting sustainability and the safety of agri-food production. In Europe, for example, the direct payment system should continue to finance agricultural practices but with greater emphasis on biosecurity that protect the environment, animal and human health. A fundamental step would be to condition direct payments on the adoption, by governments, of monitoring systems such as the Italian ClassyFarm (Tomassone et al., 2024), which should also be extended to environmental and wildlife health risks. Farm biosecurity surveillance should be strengthened, as has already been done for antibiotic use and animal health. Research should intensify its efforts to set indicators defining clear cause-and-effect relationships between the practices adopted and the reduction of health risks, to be used for farm monitoring. Furthermore, the creation of a general framework for national biosecurity strategies in animal farming should be promoted following established examples, such as the FAO's Progressive Management Pathway for Antimicrobial Resistance (FAO, 2025). This institutional capacity-building process will be crucial in increasing the effectiveness of biosecurity at the global level, ensuring that all measures adopted in different countries align, at least, with minimum international standards. Finally, strengthening the understanding of farmers, veterinarians, and the general public regarding biosecurity, through awareness campaigns and professional training, is essential to ensure full and correct implementation of policies. Awareness, combined with the introduction of targeted financial incentives, will allow for better adaptation of agricultural producers to biosecurity regulations ensuring economic sustainability. The effectiveness of prevention and health emergency management policies in the agricultural sector is hindered by several structural challenges. For example, in Europe the implementation of regulations is often inconsistent, particularly at the local level, due to differing operational capacities and uneven resource allocation among Member States. These issues are compounded by significant gaps in data sharing and integration, including deficiencies in communication flows and the exchange of surveillance information across countries.

A limitation of this study is the relatively small number of studies included in the analysis, which may reflect the fact that the field of biosecurity, particularly from an economic perspective, is still in its early stages. This trend is evident in the bibliometric analysis, which shows a recent increase in publications on this subject. Another limitation pertains to the number of articles included in the content analysis. Only 25 out of 586 studies were analysed, as the focus was specifically on those that provided quantitative data related to the costs of biosecurity measures. However, the selection of these 25 studies was carried out independently by three different researchers, followed by a briefing session with additional experts to compare and validate the results, ensuring a rigorous and objective selection process. Another limitation of the study is that systematically synthesizes the available cost data, highlighting the critical lack of effectiveness estimates in the literature. Consequently, there are no formal cost-effectiveness analyses available: while several studies report costs of implementing biosecurity measures, robust and comparable estimates of disease risk reduction are lacking. Such effectiveness data are essential for cost-effectiveness modeling. In the absence of empirical or model-based links between biosecurity measures and measurable health outcomes (e.g., risk reduction, cases averted, or disease incidence), cost-effectiveness ratios and standard economic evaluations cannot be reliably conducted. Addressing these gaps should be a priority for future research.

Many relevant studies have been published in journals focused on veterinary medicine, animal health, and animal diseases. Despite the emerging interest in biosecurity, a significant gap in specialized journals focusing on the economic aspects of animal biosecurity remains. This suggests that the economic dimension of biosecurity is still underexplored, presenting an opportunity for further research. Additionally, the growing trend of intercontinental collaboration among authors reflects a more global approach to addressing the challenges and opportunities in biosecurity research. A notable gap in the literature remains regarding the economic aspects of biosecurity in intensive pig farming. This highlights the need for a more comprehensive understanding of how to optimize spending, both in terms of activity levels and specific biosecurity measures (Kompas et al., 2015). A further significant gap in literature concerns the lack of an integrated framework of biosecurity, animal health, welfare, and performance, which have been extensively studied individually than as an interconnected dimension. A holistic approach could uncover the interconnections between these areas. It is essential to tailor biosecurity measures to specific risks, available resources, and socioeconomic conditions that differ across countries and regions. To address this research gap, future studies should focus on quantifying the economic impacts of biosecurity practices in intensive pig farming. Based on the findings of this study, the costs associated with structural adjustments have been insufficiently explored in the literature; in contrast, several studies have focused primarily on business practices. Future research should prioritize examining how the operational efficiency of facilities influences the costs of implementing biosecurity measures. This is crucial for the development of effective and sustainable biosecurity policies and practices. Indeed, when facilities are designed to optimize biosecurity management and minimize contamination risks, the overall costs are likely to decrease, as the incidence of diseases or epidemics requiring additional containment measures is reduced. Additionally, future studies should pay particular attention to the biosecurity costs faced by small-scale farms. While these farms may not have high production volumes, they are often highly vulnerable to infection and contagion risks, which could have catastrophic consequences not only for individual farms but also for the broader agricultural and livestock sectors. Finally, through the use of tools for biosecurity assessments, it would be possible to identify the most at-risk farms, enabling targeted support in the form of subsidies, low-interest loans, or tax incentives to help farmers cover the initial costs of implementing biosecurity measures.

Ensuring the sustainability of biosecurity measures is crucial from both economic and social perspectives. A comprehensive approach to biosecurity in swine farms must also consider economic aspects. This research aims to identify best practices, assess potential returns on investment, and determine the most cost-effective strategies for leveraging biosecurity to increase overall farm profitability and sustainability.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material and in the Zenodo repository (DOI:10.5281/zenodo.17047612). Further inquiries can be directed to the corresponding author.

Author contributions

VS: Conceptualization, Investigation, Writing – original draft, Visualization, Validation, Formal analysis, Writing – review & editing, Methodology, Data curation. GA: Conceptualization, Validation, Methodology, Data curation, Investigation, Writing – review & editing, Writing – original draft, Visualization, Formal analysis. CR: Investigation, Writing – review & editing, Data curation, Formal analysis. MA: Validation, Investigation, Project administration, Funding acquisition, Writing – review & editing, Supervision. MC: Investigation, Writing – review & editing, Writing – original draft, Supervision, Conceptualization, Methodology, Validation, Funding acquisition.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This work was funded by the European Union under the Horizon Europe grant 101083923 (BIOSECURE). Views and opinions expressed are those of the authors only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Acknowledgments

We wish to express our sincere gratitude to all the researchers who are currently involved in, or have previously participated in, the European Project BIOSECURE. Their valuable information and advice have, either directly or indirectly, significantly contributed to the progress of this research.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. During the preparation of this work, the authors used OpenAI's generative artificial intelligence chatbot "ChatGTP" to support the drafting and refinement of certain sections of the text. The tool was used under the supervision of the authors to assist with language editing, paraphrasing, and improving clarity. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fanim.2026.1738787/full#supplementary-material

References

Agnusdei, G. P., and Coluccia, B. (2022). Sustainable agrifood supply chains: Bibliometric, network and content analyses. *Sci. Tot. Environ.* 824, 153704. doi: 10.1016/j.scitotenv.2022.153704

Alarcón, L. V., Allepuz, A., and Mateu, E. (2021). Biosecurity in pig farms: a review. *Porc Health Manage.* 7, 5. doi: 10.1186/s40813-020-00181-z

Alonso, C., Murtaugh, M. P., Dee, S. A., and Davies, P. R. (2013). Epidemiological study of air filtration systems for preventing PRRSV infection in large sow herds. *Prev. Vet Med.* 112, 109–117. doi: 10.1016/j.prevetmed.2013.06.001

Amass, S. F. (1999). Biosecurity considerations for pork production units. *Swine Health Prod.* 7(5), 217–228. Available online at: https://www.aasv.org/shap/issues/v7n5/v7n5p217.pdf (Accessed March 16, 2026).

Amass, S. F., Stover, J. H., and Beaudry, D. J. (2000). Evaluating the efficacy of boot baths in biosecurity protocols. *Swine Health Prod.* 8(4), 169–173. Available online at: https://www.aasv.org/shap/issues/v8n4/v8n4p169.pdf (Accessed March 16, 2026).

Aria, M., and Cuccurullo, C. (2017). bibliometrix : An R-tool for comprehensive science mapping analysis. *J. Informetr.* 11, 959–975. doi: 10.1016/j.joi.2017.08.007

Baptista, F. M., Alban, L., Ersbøll, A. K., and Nielsen, L. R. (2009). Factors affecting persistence of high Salmonella serology in Danish pig herds. *Prev. Vet Med.* 92, 301–308. doi: 10.1016/j.prevetmed.2009.08.005

Bâtie, C., Tran Minh, H., Thi Vu, V. A., Thuy Luong, D., Thi Pham, T., Fortané, N., et al. (2023). Reducing antimicrobial use in chicken production in Vietnam: Exploring the systemic dimension of change. *PloS One* 18, e0290296. doi: 10.1371/journal.pone.0290296

Berends, J., Bendita Da Costa Jong, J., Cooper, T. L., Dizyee, K., Morais, O., Pereira, A., et al. (2021). Investigating the socio-economic and livelihoods impacts of african swine fever in Timor-Leste: an application of spatial group model building. *Front. Vet. Sci.* 8, 687708. doi: 10.3389/fvets.2021.687708

Burton, R. J. F., Kuczera, C., and Schwarz, G.. (2008). Exploring Farmers' Cultural Resistance to Voluntary Agri-environmental Schemes. *Sociol. Ruralis* 48(1), 16–37. doi: 10.1111/j.1467-9523.2008.00452.x

Casal, J., De Manuel, A., Mateu, E., and Martín, M. (2007). Biosecurity measures on swine farms in Spain: Perceptions by farmers and their relationship to current on-farm measures. *Prev. Vet Med.* 82, 138–150. doi: 10.1016/j.prevetmed.2007.05.012

Christensen, L. S., Mousing, J., Mortensen, S., Soerensen, K. J., Strandbygaard, S. B., Henriksen, C. A., et al. (1990). Evidence of long distance airborne transmission of Aujeszky's disease (pseudorabies) virus. *Vet. Rec.* 127, 471–474.

Collineau, L., Rojo-Gimeno, C., Léger, A., Backhans, A., Loesken, S., Nielsen, E. O., et al. (2017). Herd-specific interventions to reduce antimicrobial usage in pig production without jeopardising technical and economic performance. *Prev. Vet Med.* 144, 167–178. doi: 10.1016/j.prevetmed.2017.05.023

Corzo, C. A., Mondaca, E., Wayne, S., Torremorell, M., Dee, S., Davies, P., et al. (2010). Control and elimination of porcine reproductive and respiratory syndrome virus. *Virus Res.* 154, 185–192. doi: 10.1016/j.virusres.2010.08.016

Dee, S. A., Deen, J., Otake, S., and Pijoan, C. (2004). An experimental model to evaluate the role of transport vehicles as a source of transmission of porcine reproductive and respiratory syndrome virus to susceptible pigs. *Can. J. Vet. Res.* 68, 128–133. Available online at: https://pmc.ncbi.nlm.nih.gov/articles/PMC1142156/pdf/cjvr68pg128.pdf (Accessed March 16, 2026).

Dione, M., Masembe, C., Akol, J., Amia, W., Kungu, J., Lee, H. S., et al. (2018). The importance of on-farm biosecurity: Sero-prevalence and risk factors of bacterial and viral pathogens in smallholder pig systems in Uganda. *Acta Tropica* 187, 214–221. doi: 10.1016/j.actatropica.2018.06.025

Donthu, N., Kumar, S., Pattnaik, D., and Lim, W. M. (2021). A bibliometric retrospection of marketing from the lens of psychology: Insights from *Psychology & Marketing*. *Psychol. Market* 38, 834–865. doi: 10.1002/mar.21472

Dors, A., Czyżewska, E., Pomorska-Mól, M., Kołacz, R., and Pejsak, Z.. (2013). Effect of various husbandry conditions on the production parameters of swine herds in Poland. *Pol. J. Vet. Sci.* 16(4), 707–713. doi: 10.2478/pjvs-2013-0100

Fahimnia, B., Tang, C. S., Davarzani, H., and Sarkis, J. (2015). Quantitative models for managing supply chain risks: A review. *Eur. J. Oper Res.* 247, 1–15. doi: 10.1016/j.ejor.2015.04.034

FAO. (2025). *The FAO Progressive Management Pathway for Antimicrobial Resistance - User's manual.* Rome: FAO. doi: 10.4060/cd4910en

Fasina, F. O., Lazarus, D. D., Spencer, B. T., Makinde, A. A., and Bastos, A. D. S. (2012). Cost implications of african swine fever in smallholder farrow-to-finish units: economic benefits of disease prevention through biosecurity: cost implications of african swine fever. *Transbound Emerg Dis* 59, 244–255. doi: 10.1111/j.1865-1682.2011.01261.x

Fedorka-Cray, P. J., Hogg, A., Gray, J. T., Lorenzen, K., and Behren, P. V. (1997). Feed and feed trucks as sources of Salmonella contamination in swine. *Swine Health Prod.* 5 (5), 189–193. Available online at: https://www.aasv.org/shap/issues/v5n5/v5n5p189.html (Accessed March 16, 2026).

Fraser, R. W., Williams, N. T., Powell, L. F., and Cook, A. J. C. (2010). Reducing campylobacter and *salmonella* infection: two studies of the economic cost and attitude to adoption of on-farm biosecurity measures. *Zoonoses Public Health* 57, 109–115. doi: 10.1111/j.1863-2378.2009.01295.x

Garforth, C. J., Bailey, A. P., and Tranter, R. B. (2013). Farmers' attitudes to disease risk management in England: A comparative analysis of sheep and pig farmers. *Prev. Vet Med.* 110, 456–466. doi: 10.1016/j.prevetmed.2013.02.018

Garousi, V., and Fernandes, J. M. (2017). Quantity versus impact of software engineering papers: a quantitative study. *Scientometrics.* 112, 963–1006. doi: 10.1007/s11192-017-2419-6

Garrido-Mantilla, J., Lara, A., Guardado, E., Lopez, J., Nerem, J., Pizarro, G., et al. (2022). Feed or feed transport as a potential route for a porcine epidemic diarrhoea outbreak in a 10,000-sow breeding herd in Mexico. *Transbound. Emerg. Dis.* 69, 66–71. doi: 10.1111/tbed.14354

Gohin, A., and Rault, A. (2013). Assessing the economic costs of a foot and mouth disease outbreak on Brittany: A dynamic computable general equilibrium analysis. *Food Policy* 39, 97–107. doi: 10.1016/j.foodpol.2013.01.003

Hauser, C. E., and McCarthy, M. A. (2009). Streamlining 'search and destroy': cost-effective surveillance for invasive species management. *Ecol. Lett* 12, 683–692. doi: 10.1111/j.1461-0248.2009.01323.x

Hennessy, D. A., Roosen, J., and Jensen, H. H. (2005). Infectious disease, productivity, and scale in open and closed animal production systems. *Am. J. Agri Econ.* 87, 900–917. doi: 10.1111/j.1467-8276.2005.00777.x

Higgins, V., Bryant, M., Hernández-Jover, M., Rast, L., and McShane, C. (2018). Devolved responsibility and on-farm biosecurity: practices of biosecure farming care in livestock production. *Sociol Ruralis* 58, 20–39. doi: 10.1111/soru.12155

Isomura, R., Matsuda, M., and Sugiura, K. (2018). An epidemiological analysis of the level of biosecurity and animal welfare on pig farms in Japan and their effect on the use of veterinary antimicrobials. *J. Vet Med. Sci* 80, 1853–1860. doi: 10.1292/jvms.18-0287

Ivanova, P., and Ivanova, E. (2019). Economic model for calculation of direct and indirect economical losses from African swine fever occurrence. *BJVM.* 22, 227–236. doi: 10.15547/bjvm.2037

Jiménez-Ruiz, S., Laguna, E., Vicente, J., García-Bocanegra, I., Martínez-Guijosa, J., Cano-Terriza, D., et al. (2022). Characterization and management of interaction risks between livestock and wild ungulates on outdoor pig farms in Spain. *Porc Health Manage.* 8, 2. doi: 10.1186/s40813-021-00246-7

Kompas, T., Nguyen, H. T. M., and Ha, P. V. (2015). Food and biosecurity: livestock production and towards a world free of foot-and-mouth disease. *Food Sec* 7, 291–302. doi: 10.1007/s12571-015-0436-y

Laanen, M., Persoons, D., Ribbens, S., De Jong, E., Callens, B., Strubbe, M., et al. (2013). Relationship between biosecurity and production/antimicrobial treatment characteristics in pig herds. *Vet J.* 198, 508–512. doi: 10.1016/j.tvjl.2013.08.029

Ladoşi, I., Păpuc, T. A., and Ladoşi, D. (2023). The impact of african swine fever (ASF) on Romanian pig meat production: A review. *Acta Vet* 73, 1–12. doi: 10.2478/acve-2023-0001

Layton, D. S., Choudhary, A., and Bean, A. G. D. (2017). Breaking the chain of zoonoses through biosecurity in livestock. *Vaccine.* 35, 5967–5973. doi: 10.1016/j.vaccine.2017.07.110

Lurette, A., Touzeau, S., Ezanno, P., Hoch, T., Seegers, H., Fourichon, C., et al. (2011). Within-herd biosecurity and Salmonella seroprevalence in slaughter pigs: A simulation study. *J. Anim. Sci* 89, 2210–2219. doi: 10.2527/jas.2010-2916

Maditati, D. R., Munim, Z. H., Schramm, H. J., and Kummer, S. (2018). A review of green supply chain management: From bibliometric analysis to a conceptual framework and future research directions. *Resour. Conserv. Recycl.* 139, 150–162. doi: 10.1016/j.resconrec.2018.08.004

Nathues, H., Alarcon, P., Rushton, J., Jolie, R., Fiebig, K., Jimenez, M., et al. (2018). Modelling the economic efficiency of using different strategies to control Porcine Reproductive & Respiratory Syndrome at herd level. *Prev. Vet Med.* 152, 89–102. doi: 10.1016/j.prevetmed.2018.02.005

Niemi, J., Bennett, R., Clark, B., Frewer, L., Jones, P., Rimmler, T., et al. (2020). A value chain analysis of interventions to control production diseases in the intensive pig production sector. *PloS One* 15, e0231338. doi: 10.1371/journal.pone.0231338

Niemi, J. K., Sahlström, L., Kyyrö, J., Lyytikäinen, T., and Sinisalo, A. (2016). Farm characteristics and perceptions regarding costs contribute to the adoption of biosecurity in Finnish pig and cattle farms. *Rev. Agric. Food Environ. Stud.* 97, 215–223. doi: 10.1007/s41130-016-0022-5

Ospina-Pinto, C., Rincon-Pardo, M., Soler-Tovar, D., and Hernández-Rodríguez, P. (2017). Papel de los roedores en la transmisión de Leptospira spp. en granjas porcinas. *Rev. Salud Pública* 19, 555–561. doi: 10.15446/rsap.v19n4.41626

Otake, S., Dee, S., Corzo, C., Oliveira, S., and Deen, J. (2010). Long-distance airborne transport of infectious PRRSV and Mycoplasma hyopneumoniae from a swine population infected with multiple viral variants. *Vet Microbiol.* 145, 198–208. doi: 10.1016/j.vetmic.2010.03.028

Ouma, E., Dione, M., Birungi, R., Lule, P., Mayega, L., and Dizyee, K. (2018). African swine fever control and market integration in Ugandan peri-urban smallholder pig value chains: An ex-ante impact assessment of interventions and their interaction. *Prev. Vet Med.* 151, 29–39. doi: 10.1016/j.prevetmed.2017.12.010

Pao, H. N. I., Jackson, E., Yang, T.S., Tsai, J.S., Sung, W. H. T., and Pfeiffer, D. U. (2022). Determinants of farmers' biosecurity mindset: A social-ecological model using systems thinking. *Front. Vet. Sci.* 9, 959934. doi: 10.3389/fvets.2022.959934

Pham, H. T. T., Antoine-Moussiaux, N., Grosbois, V., Moula, N., Truong, B. D., Phan, T. D., et al. (2017). Financial impacts of priority swine diseases to pig farmers in red river and mekong river delta, Vietnam. *Transbound Emerg. Dis.* 64, 1168–1177. doi: 10.1111/tbed.12482

Polaček, V., Mirčeta, J., and Prodanov-Radulović, J. (2021). Key risk factors and impact of African swine fever spreading on pig production in Serbia. *Acta Vet* 71, 371–391. doi: 10.2478/acve-2021-0032

Postma, M., Backhans, A., Collineau, L., Loesken, S., Sjölund, M., Belloc, C., et al. (2016a). Evaluation of the relationship between the biosecurity status, production parameters, herd characteristics and antimicrobial usage in farrow-to-finish pig production in four EU countries. *Porc Health Manage.* 2, 9. doi: 10.1186/s40813-016-0028-z

Postma, M., Backhans, A., Collineau, L., Loesken, S., Sjölund, M., Belloc, C., et al. (2016b). The biosecurity status and its associations with production and management characteristics in farrow-to-finish pig herds. *Animal.* 10, 478–489. doi: 10.1017/S1751731115002487

Qaiser, F. H., Ahmed, K., Sykora, M., Choudhary, A., and Simpson, M. (2017). Decision support systems for sustainable logistics: a review and bibliometric analysis. *IMDS.* 117, 1376–1388. doi: 10.1108/IMDS-09-2016-0410

Rodrigues Da Costa, M., Gasa, J., Calderón Díaz, J. A., Postma, M., Dewulf, J., McCutcheon, G., et al. (2019). Using the Biocheck.UGent™ scoring tool in Irish farrow-to-finish pig farms: assessing biosecurity and its relation to productive performance. *Porc. Health Manage.* 5, 4. doi: 10.1186/s40813-018-0113-6

Rojo-Gimeno, C., Postma, M., Dewulf, J., Hogeveen, H., Lauwers, L., and Wauters, E. (2016). Farm-economic analysis of reducing antimicrobial use whilst adopting improved management strategies on farrow-to-finish pig farms. *Prev. Vet Med.* 129, 74–87. doi: 10.1016/j.prevetmed.2016.05.001

Rowlands, R. J., Michaud, V., Heath, L., Hutchings, G., Oura, C., Vosloo, W., et al. (2008). African swine fever virus isolate, Georgia, 2007. *Emerg. Infect. Dis.* 14, 1870–1874. doi: 10.3201/eid1412.080591

Saegerman, C., Dal Pozzo, F., and Humblet, M. F. (2014). Reducing hazards for humans from animals: emerging and re-emerging zoonoses. *Ital. J. Public Health* 9(2), 13-22. doi: 10.2427/6336 Available online at: https://riviste.unimi.it/index.php/ijphjournal/article/view/22725.

Shortall, O., Green, M., Brennan, M., Wapenaar, W., and Kaler, J. (2017). Exploring expert opinion on the practicality and effectiveness of biosecurity measures on dairy farms in the United Kingdom using choice modeling. *J. Dairy Sci* 100, 2225–2239. doi: 10.3168/jds.2016-11435

Simoes, N., and Crespo, N. (2020). A flexible approach for measuring author-level publishing performance. *Scientometrics.* 122, 331–355. doi: 10.1007/s11192-019-03278-7

Stanojevic, S., Valcic, M., Stanojevic, S., Radojicic, S., Avramov, S., and Tambur, Z. (2015). Simulation of a classical swine fever outbreak in rural areas of the Republic of Serbia. *Vet. Med.* 60, 553–566. doi: 10.17221/8494-VETMED

Stevenson, G. W., Hoang, H., Schwartz, K. J., Burrough, E. R., Sun, D., Madson, D., et al. (2013). Emergence of *Porcine epidemic diarrhea virus* in the United States: clinical signs, lesions, and viral genomic sequences. *J. Vet. Diagn. Invest* 25, 649–654. doi: 10.1177/1040638713501675

Strozzi, F., Colicchia, C., Creazza, A., and Noè, C. (2017). Literature review on the 'Smart Factory' concept using bibliometric tools. *Int. J. Prod Res.* 55, 6572–6591. doi: 10.1080/00207543.2017.1326643

Suijkerbuijk, A. W. M., Over, E. A. B., Opsteegh, M., Deng, H., Gils, P. F. V., Bonačić Marinović, A. A., et al. (2019). A social cost-benefit analysis of two One Health interventions to prevent toxoplasmosis. *PloS One* 14, e0216615. doi: 10.1371/journal.pone.0216615

Thompson, K. M., and Tebbens, R. J. D. (2007). Eradication versus control for poliomyelitis: an economic analysis. *Lancet* 369, 1363–1371. doi: 10.1016/S0140-6736(07)60532-7

Tomassone, L., Scali, F., Formenti, N., Alborali, G. L., Aragrande, M., Canali, M., et al. (2024). Evaluation of 'ClassyFarm', the Italian integrated surveillance system of livestock farms, in the context of antimicrobial use and antimicrobial resistance. *Ital. J. Anim. Sci.* 23, 1426–1438. doi: 10.1080/1828051X.2024.2407092

van Eck, N. J., and Waltman, L.. (2009). How to normalize cooccurrence data? An analysis of some well-known similarity measures. *J. Am. Soc. Inf. Sci.* 60(8), 1635–1651. doi: 10.1002/asi.21075

Waltman, L., Van Eck, N. J., and Noyons, E. C. M. (2010). A unified approach to mapping and clustering of bibliometric networks. *J. Inform* 4, 629–635. doi: 10.1016/j.joi.2010.07.002

Weng, L., Weersink, A., Poljak, Z., De Lange, K., and Von Massow, M. (2016). An economic evaluation of intervention strategies for Porcine Epidemic Diarrhea (PED). *Prev. Vet Med.* 134, 58–68. doi: 10.1016/j.prevetmed.2016.09.018

Woeste, K., and Grosse Beilage, E. (2007). Transmission of agents of the porcine respiratory disease complex (PRDC) between swine herds: a review. Part 2-Pathogen transmission via semen, air and living/nonliving vectors. *Dtsch. Tierarztl. Wochenschr.* 114, 364–366.

Zhang, A., Young, J. R., Suon, S., Ashley, K., Windsor, P. A., and Bush, R. D. (2017). Investigating the financial impact of porcine reproductive and respiratory syndrome on smallholder pig farmers in Cambodia. *Trop. Anim. Health Prod.* 49, 791–806. doi: 10.1007/s11250-017-1264-1

Zhou, X., Li, N., Luo, Y., Liu, Y., Miao, F., Chen, T., et al. (2018). Emergence of african swine fever in China, 2018. *Transbound Emerg. Dis.* 65, 1482–1484. doi: 10.1111/tbed.12989

Zupic, I., and Čater, T. (2015). Bibliometric Methods in Management and Organization. *Organ. Res. Methods* 18(3), 429–472. doi: 10.1177/1094428114562629