Livestock and Animal Research

Accredited by Directorate General of Higher Education, Research, and Technology No. 152/E/KPT/2023

Open Access
Livest. Anim. Res., June 2026, 24(2): 10-22
p-ISSN 2721-5326 e-ISSN 2721-7086
https://doi.org/10.20961/lar.v22i3.84171

Original Article

Assessment of Biosecurity Implementation Using a Scoring System across Different Production Systems and Scales in Pig Farms of East Sumba

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Received: April 28th, 2026; Accepted: May 29th, 2026 Published online: June 24th, 2026

Abstract

Objective: Demand for pork and pigs continue to rise in line with the population growth and changing consumption patterns. To meet this demand, the expansion of production scale and improvement of efficiency have become inevitable. However, efforts to meet the increasing demand are challenged by the outbreak of pig diseases, which disrupt production and reduce livestock productivity. One of the key aspects in enhancing livestock productivity and sustainability is the implementation of biosecurity. This study aims to to analyze variations in biosecurity implementation based on production system and farm scale, using a likert score-based approach, in order to provide a scientific basis for developing strategies to improve biosecurity and disease control at the local level.
Methods: This study employed a cross-sectional design by interviewing 115 pig farmers in East Sumba regency in East Nusa Tenggara. Biosecurity scores were assessed using 5-1 likert scale, where higher scores indicated stricter biosecurity implementation. Data of the biosecurity scores were analysed using SAS on demand for Academics. Ordinal data were analyzed with a generalized linear mix model.
Results: The results showed that intensive farming system had higher biosecurity yet moderate score compare to semi-intensive and extensive systems while the production scale had no significant effect on biosecurity scores.
Conclusions: Considering the higher score was just fair/neutral, pathogens invasion was still relatively easy, suggesting short and long-term investment support must be taken to improve biosecurity score for all the pig farm regardless the production systems and production scale.

Keywords: Biosecurity implementation; Disease outbreak; Farm scale; Pig farming; Production system.

INTRODUCTION

Pig farming is a highly important livestock sector for the people of East Sumba, Indonesia, with approximately 35% of households engaged in pig rearing [1]. For local communities, pigs are not only a source of primary or supplementary income but also function as financial security, savings assets, and a medium of exchange. In addition, pigs hold a central role in socio-cultural life, particularly in traditional ceremonies such as funerals, weddings, and reconciliation rituals [2,3]. As a result, pig production in East Sumba is deeply embedded in both the economic and cultural systems of the region. This multifunctional role positions pigs as a strategic livestock commodity that contributes to the achievement of the Sustainable Development Goals (SDGs), especially Goal 1 (No Poverty) and Goal 2 (Zero Hunger).

The demand for pork and live pigs has continued to increase in recent years, driven by population growth, urbanization, and changing consumption patterns. To respond to this growing demand, pig production systems are under pressure to expand in scale and improve efficiency while maintaining sustainability. One of the key components in achieving sustainable livestock production is the implementation of biosecurity. Biosecurity refers to a set of management and hygiene measures designed to prevent the introduction, establishment, and spread of infectious pathogens within and between farms [4]. In practical terms, biosecurity encompasses actions such as controlling animal movement, maintaining sanitation, managing farm visitors, and reducing contact between domestic animals and potential disease sources. Numerous studies have shown that effective biosecurity implementation can significantly reduce disease incidence, improve animal health and productivity, and minimize economic losses associated with disease outbreaks [5].

Despite its recognized importance, the adoption and implementation of biosecurity measures vary considerably among pig farms. Existing literature indicates that biosecurity practices are influenced by multiple factors, including resource availability, farmer knowledge and attitudes, perceived disease risk, and the strength of institutional and regulatory frameworks [6,7]. Among these factors, production system and farm scale have consistently been identified as major determinants of biosecurity adoption. Intensive production systems, which are typically characterized by confined housing, controlled feeding regimes, and routine health monitoring, tend to exhibit higher levels of biosecurity compliance. In contrast, extensive or traditional systems often rely on free-range or semi-free-range management, increasing the likelihood of contact with other animals, contaminated environments, and disease vectors [8,9].

Farm scale further shapes biosecurity implementation. Large-scale commercial farms generally have greater access to financial capital, veterinary services, technical knowledge, and infrastructure, allowing them to apply biosecurity measures in a more systematic and consistent manner. Smallholder farms, on the other hand, often face constraints related to limited resources, labor shortages, and competing livelihood priorities, which can hinder the adoption of recommended biosecurity practices [10,11]. While these patterns are well documented in many regions, much of the existing research has focused on commercial or semi-commercial pig systems, particularly in high-income countries or areas with relatively advanced veterinary infrastructure.

In East Sumba, the pig sector is dominated by smallholder farmers who largely operate under traditional or semi-traditional production systems. These systems often lack structured housing, controlled animal movement, and standardized health management practices. Consequently, the level of biosecurity implementation remains generally low, increasing the vulnerability of pig populations to infectious diseases. This vulnerability has been clearly demonstrated by the recurrent occurrence of major transboundary and endemic diseases, including African Swine Fever (ASF), Classical Swine Fever, and Foot-and-Mouth Disease (FMD). Since 2020, ASF has been reported as an annual outbreak in East Sumba, resulting in the death of tens of thousands of pigs and causing severe economic and social impacts on farming households [12,13]. These repeated outbreaks indicate persistent weaknesses in disease prevention and control, both at the farm level and within the broader regional livestock system.

Although biosecurity is widely recognized as a cornerstone of disease prevention, there remains a limited empirical understanding of how biosecurity practices are actually implemented across different production systems and farm scales in smallholder-dominated regions such as East Sumba. Existing studies rarely provide detailed, comparative assessments within a single high-risk area, particularly in contexts where pig production is closely intertwined with cultural practices and informal management systems. This lack of location-specific evidence constrains the development of realistic and context-appropriate biosecurity interventions, as recommendations derived from intensive or commercial settings may not be directly applicable to smallholder conditions.

Given the socio-economic and cultural importance of pigs in East Sumba, combined with the high and recurring risk of infectious disease outbreaks, there is a clear need for a systematic assessment of biosecurity implementation in the region. A better understanding of how biosecurity varies according to production system and farm scale is essential for identifying critical gaps, prioritizing interventions, and designing disease control strategies that are both effective and feasible for local farmers. Therefore, the aim of this study is to analyze variations in biosecurity implementation among pig farms in East Sumba based on production system (intensive, semi-intensive, and extensive) and farm scale, using a score-based assessment approach. By generating empirical, location-specific evidence, this study provides a scientific basis for improving biosecurity planning and strengthening disease prevention strategies tailored to smallholder pig production systems in East Sumba.

MATERIALS AND METHODS

Study Subjects and Location

The study was conducted between June and August 2025 in East Sumba Regency, East Nusa Tenggara, Indonesia. The subjects or respondents in this study were 115 pig farmers from six districts, namely Kambera, Kanatang, Lewa, Umalulu, Haharu, and Rindi. The selection of these locations was based on accessibility, population density, and livestock population, which may influence the adoption of livestock production systems and production scales. Kambera district is classified as an urban area with a population density of 671 people/km^2 and the largest number of pig farmers (2,299). Umalulu, Lewa, and Kanatang are peri-urban areas with population densities of 60, 56, and 39 people/km^2, respectively, and with 1,643, 1,677, and 1,221 pig farmers, respectively. Rindi and Haharu represent rural areas with lower population densities of 27 and 11 people/km^2 and 1,180 and 855 pig farmers, respectively [14,15]. Based on this information, six respondents were selected from each of the five villages or urban wards in Kambera; four respondents from each of the five villages in Umalulu, Lewa, and Kanatang; and three respondents from each of the five villages in Rindi and two respondents from each of the five villages in Haharu (Table 1). Data on the presence of pig farmers were obtained from the respective village or ward offices. Prior to data collection, informed consent was obtained from all the participants and participation was voluntary. All data were anonymized to ensure confidentiality.

Research Methods

This study employed a cross-sectional design involving interviews with pig farmers to obtain data on demographic characteristics, production systems, production scales, and biosecurity practices among pig farms in East Sumba. Primary data were collected directly from livestock owners through questionnaire-based interviews and direct observation of farm conditions and management practices. The respondents included pig farmers managing both commercial and non-commercial pig farms.

The dependent variable in this study was the biosecurity score, which varied across production systems. The independent variables were the pig production system—classified into three categories (extensive, semi-intensive, and intensive)—and production scale (large and small). The classification of production scale was based on the number of pigs kept by households in East Sumba. The average herd size in East Sumba was five pigs per household [15,16]. Accordingly, farms with six or more pigs were categorized as large-scale, whereas farms with fewer than six pigs were categorized as small-scale. It should be emphasized that the terms “large-scale” and “small-scale” in this study represent a relative classification within the context of smallholder pig farming systems in East Sumba, rather than an absolute commercial or industrial production standard.

The relatively low threshold reflects the substantial decline in pig populations in the region due to recurrent ASF outbreaks in recent years [13].

Table 1. Sampling Location

No	District	Village/sub-district*	Number of respondents
1	Kambera	**Wangga** **Lambanapu** **Maulumbi** **Kambaniru** **Mauhau**	6 respondents per sub-district
2	Lewa	**Lewapaku** Kambata Wundut Kondamara Kambuhapang Tanarara	4 respondents per village/sub-district
3	Haharu	Napu Wunga Kadahang Rambangaru Praibakul	2 respondents per village
4	Kanatang	Mondu Hambapraing Kuta **Temu** Pambotanjara**	4 respondents per village/sub-district
5	Umalulu	Wanga Patawang Matawai Atu Watu Hadang Lairuru	4 respondents per village
6	Rindi	Kayuri Tanaraing Haikatapu Kabaru Rindi	3 respondents per village

*The locations highlighted in bold are sub-districts

** The village is administratively part of Kota Waingapu Subdistrict; however, geographically, it borders Kanatang Subdistrict.

Regarding biosecurity practices, the questionnaire was designed in the form of structured questions with multiple-choice options, using a Likert scale method. Farmers' responses were assigned scores ranging from 5 to 1, with answer alternatives adjusted according to each question [17]. A higher score indicated stricter implementation of biosecurity practices on the farm. The scoring system for respondents' answers using the Likert scale (Table 2).

Questions related to respondent demographics included age, educational attainment, years of farming experience, primary occupation, production scale, and ownership of other livestock. The questionnaire on biosecurity practices was divided into three levels: conceptual, structural, and operational. Conceptual biosecurity indicators included (but were not limited to): distance of the farm from neighbors or residential areas, distance of pig housing from water sources, size of the farm/pig housing area, fencing or barriers separating the farm from the external environment, separation between clean, buffer, and dirty zones, separate pens for males and females, and separate housing for growth phases (starter, grower, finisher). Structural biosecurity indicators included (but were not limited to): internal housing layout, distance between pig housing and storage facilities or offices, waste management systems, availability of sanitation and decontamination equipment, disinfection techniques applied, types of disinfectants used, use of personal protective equipment (PPE) within the farm area, access restrictions to outsiders, and presence of vectors capable of transmitting pathogens. Operational biosecurity indicators included (but were not limited to): sanitation procedures for animals and humans entering or leaving the farm, availability of veterinary or extension services in the vicinity, management of sick animals, carcass disposal practices, type of feed (commercial or non-commercial), feed treatment, water sources for drinking and sanitation, availability of isolation pens, and vaccination practices [11,17].

Table 2. Likert Scale Scoring System

Score	Response Option
1	Very poor/Strongly Disagree
2	Poor/Disagree
3	Neutral/Fair
4	Good/Agree
5	Very Good/Strongly Agree

Data Analysis

Data of the biosecurity score were analysed using SAS on demand for Academics (SAS Inst. Inc., Cary, NC). Data from each biosecurity aspect were expressed as averages calculated from multiple observed questions. Ordinal data were analysed with a generalized linear mixed model (analysis with PROC GLIMMIX).

The model used to analyse the data was as the following:

Y = μ + production system$i$ + production scale$j$+ (system$i$ × scale$j$); with district$k$ as a random effect.

Where: Y = the dependent variable, μ is the overall mean, production system= type of the system adopted at the farm (i=intensive, semi-intensif or extensive), production scale (j = small or big), district (k = 1, 2, 3, 4, 5, 6). Data are expressed in LS Means. Effects and interactions were considered significant when $P \leq 0.05$, where pairwise comparisons were done with Tukey-Kramer test. A prior power calculation was not performed because the study was exploratory and based on the available population of pig farmers in the study area.

RESULTS

Biosecurity has become an essential element of livestock production, particularly in intensive systems such as in the pig industry to avoid the introduction of new pathogens to the farm and to limit their spread within the farm. By doing so, it will contribute to increase the wellbeing of pigs, the productivity of the farms and the contribution to public health as well [18]. In this study, the implementation of biosecurity was evaluated accross different production systems and production scales to identify patterns and gaps relevant to smallholder-dominated settings.

Socio-demographic Characteristics in Relation to Pig Production Systems and Biosecurity Contex

The socio-demographic characteristics of respondents varied across intensive, semi-intensive, and extensive pig production systems, reflecting differences in labor structure, human capital, and potential capacity to implement biosecurity measures (Table 3). Intensive systems were characterized by greater participation of both men and women, indicating a more organized division of labor that may support routine farm management, including biosecurity practices. In contrast, extensive systems showed more limited female involvement, suggesting a less formalized management structure. Across all production systems, the majority of farmers were older than 40 years, accounting for 56.2%, 69.2%, and 68.8% of respondents in intensive, semi-intensive, and extensive systems, respectively. These findings indicate an aging farming population with relatively low participation from younger individuals, particularly in less intensive systems. The results are consistent with previous studies showing that pig farming is often dominated by middle-aged and older producers, while gender participation and labor availability influence the adoption of farming systems [19,20].

Clear differences were also observed in education, farming experience, and livelihood orientation. Intensive systems were associated with higher levels of formal education, with 42.5% of respondents completing senior high school and 13.7% attaining higher education, reflecting stronger access to knowledge and resources that may facilitate the adoption of improved biosecurity practices [21]. Meanwhile, semi-intensive and extensive systems were largely dominated by farmers with lower educational backgrounds and longer farming experience, indicating greater reliance on traditional knowledge and management practices. This suggests that longer farming experience does not necessarily translate into improved farming systems [22]. In addition, extensive systems tended to involve larger households, with 62.5% of respondents having more than five household dependents, suggesting a stronger dependence on family labor, which may influence the consistency and standardization of biosecurity implementation across production activities.

Table 3. Respondents characteristics in East Sumba Regency based on the production systems adopted

Characteristics	Intensive n (%)	Semi-intensive n (%)	Extensive n (%)
Gender			
Female	29 (39.7)	13 (50.0)	4 (25.0)
Male	44 (60.3)	13 (50.0)	12 (75.0)
Age			
17-40	32 (43.8)	8 (30.8)	5 (31.2)
>40	41 (56.2)	18 (69.2)	11 (68.8)
Education			
No formal education	5 (6.8)	2 (7.7)	1 (6.2)
Elementary school	15 (20.5)	12 (46.2)	10 (62.5)
Junior high school	12 (16.4)	6 (23.1)	2 (12.5)
Senior high school	31 (42.5)	3 (11.5)	3 (18.8)
Higher education	10 (13.7)	3 (11.5)	0 (0.0)
Experience in keeping pig			
1-10 years	41 (56.2)	11 (42.3)	7 (42.8)
>10 years	32 (43.8)	15 (57.7)	9 (56.2)
Main Occupations			
Farmer	49 (67.1)	21 (80.8)	13 (81.2)
Housewife	5 (6.8)	3 (11.5)	1 (.2)
Civil servant	4 (5.5)	1 (3.8)	0 (0.0)
Entrepreneur	8 (11.0)	1 (3.8)	0 (0.0)
Others	7 (9.6)	0 (0.0)	2 (12.5)
Number of dependents in household			
1-5 people	43 (58.9)	19 (73.1)	6 (37.5)
>5 people	30 (41.1)	7 (26.9)	10 (62.5)

Biosecurity Practices Across Production Systems

Table 4 presents the least square means (±SE) of biosecurity practice scores across different production systems, categorized into conceptual, structural, and operational aspects, as well as the overall score. Farmers operating under an intensive production system consistently demonstrated higher biosecurity scores in all aspects compared to those practicing semi-intensive and extensive systems. The intensive system achieved mean scores of 3.62 (conceptual), 2.33 (structural), 3.01 (operational), and 2.96 (overall), which were significantly higher ($p<0.05$) than the other systems. In contrast, semi-intensive and extensive systems showed lower and statistically similar scores, with overalls of 1.72 and 1.54, respectively.

Studies showed strong correlation between production systems and biosecurity practices. According to Alarcon et al [18], the more intensive the production system, the higher the biosecurity score, becuase different production systems result in variations of management practices, the technology used, and the awareness of biosecurity importance. In the present study, intensive production systems applied better biosecurity practices than semi-intensive and extensive systems. However, despite being statistically higher, the average biosecurity score of intensive farms (2.96) remained within the neutral or fair category, indicating that pathogen introduction was still relatively possible.

Table 4. Biosecurity practice score by production system based on likert score (LS mean± SE)

Production System	Biosecurity practice score			
	Conceptual	Structural	Operational	Overall
Intensive	3.62±0.07^{a}	2.33±0.10^{a}	3.01±0.08^{a}	2.96±0.07^{a}
Semi-intensive	2.09±0.11^{b}	1.25±0.15^{b}	1.87±0.12^{b}	1.72±0.10^{b}
Extensive	1.76±0.14^{b}	1.14±0.18^{b}	1.73±0.15^{b}	1.54±0.12^{b}

Different superscripts in the same column indicate significant differences (*p<0.05*)

Biosecurity Practices Across Production Scales

Table 5 presents the least square means (±SE) of biosecurity practice scores according to production scale, evaluated across conceptual, structural, and operational dimensions, as well as the overall score. The results indicate that biosecurity scores were comparable and there was no significant difference (p>0.05) between small- and large-scale production systems in East Sumba regency, with only minor differences observed across dimensions. Small-scale farms recorded mean scores of 2.50 (conceptual), 1.67 (structural), 2.22 (operational), and 2.12 (overall), while large-scale farms obtained 2.48, 1.47, 2.19, and 2.03, respectively. These suggested that production scale had no measurable effect on the implementation of biosecurity practices. This finding contrast with previous studies conducted in commercial and industrial farming contexts, which reported stricter biosecurity practices in larger-scale operations [18,23].

This may be attributed to the predominance of smallholder farmers in this study who lacked the capacity to allocate resources for infrastructure investment, routine maintenance and adherence to production standards. Additionally, as a high proportion of the respondents in this study raised pigs as secondary source of income, their perception of the potential profit from biosecurity measure influenced both the extent of implementation and their willingness to enforce strict practices [24]. Although larger farms may face greater potential losses during outbreaks [25], this risk did not translate into significantly higher biosecurity scores in the present study.

Table 5. Biosecurity practice score by production scale based on likert score (LS mean± SE)

Production Scale	Biosecurity practice score			
	Conceptual	Structural	Operational	Overall
Small	2.50±0.09	1.67±0.13	2.22±0.10	2.12±0.09
Large	2.48±0.08	1.47±0.11	2.19±0.09	2.03±0.08

Interaction between Production Systems and Scale on Biosecurity Practice

Table 6 presents the least square means (±SE) of biosecurity practice scores across the interaction between production system and production scale. The results demonstrate that within the intensive system, large-scale farms achieved significantly higher scores in all dimensions of biosecurity compared to small-scale farms (p<0.05). Specifically, large-scale intensive farms recorded total scores of 3.24 where value correspond to a likert score interpretation of moderate to high biosecurity implementation; particularly strong at the conceptual dimention. Its small-scale counterparts obtained 2.68, which can be interpreted as moderate biosecurity implementation, with weaker performance in structural dimention. In contrast, within the semi-intensive and extensive systems, biosecurity scores were generally low and showed no meaningful differences between small- and large-scale farms. Both show very low to low biosecurity implementation. For instance, total scores in semi-intensive systems were 1.86 (small-scale) and 1.58 (large-scale), while extensive systems recorded 1.55 and 1.53, respectively. The data indicate that the effect of production scale on biosecurity is contingent upon the production system. This was particularly evident in intensive systems, where large-scale operations differed significantly from small-scale ones, whereas in other production systems, herd size alone did not affect biosecurity practice.

Intensive farming systems in this study, either large or small scale, exhibited higher biosecurity scores, reflecting stronger awareness, knowledge, and facility support, alongside stricter housing, sanitation, and animal health management. Conversely, semi-intensive and extensive systems score lower, indicating limited infrastructure and reduced livestock supervision. These structural and managerial gaps are particularly evident among smallholder farmers, who often perceive biosecurity such as fencing and disinfection as costly, labour consuming and less urgent than daily farm. Furthermore, this cross-sectional study was conducted during dry season where there were no cases of infectious disease, further reduced the perceived urgency of implementing biosecurity.

Table 6. Interaction between production systems and Scale on Biosecurity practice based on likert score (LS mean± SE)

Production System	Production scale	Biosecurity practice score			
		Conceptual	Structural	Operational	Overall
Intensive	Small	$3.38{\pm}0.07^{a}$	$1.99{\pm}0.09^{a}$	$2.75{\pm}0.08^{a}$	$2.68{\pm}0.07^{a}$
	Large	$3.87{\pm}0.13^{b}$	$2.66{\pm}0.17^{b}$	$3.27{\pm}0.14^{b}$	$3.24{\pm}0.12^{b}$
Semi-intensive	Small	$2.23{\pm}0.13^{c}$	$1.32{\pm}0.18^{c}$	$2.08{\pm}0.14^{c}$	$1.86{\pm}0.12^{c}$
	Large	$1.95{\pm}0.18^{c}$	$1.18{\pm}0.24^{c}$	$1.65{\pm}0.19^{c}$	$1.58{\pm}0.16^{c}$
Extensive	Small	$1.84{\pm}0.21^{c}$	$1.11{\pm}0.28^{c}$	$1.74{\pm}0.22^{c}$	$1.55{\pm}0.19^{c}$
	Large	$1.68{\pm}0.18^{c}$	$1.18{\pm}0.24^{c}$	$1.73{\pm}0.19^{c}$	$1.53{\pm}0.16^{c}$

Different superscripts in the same column indicate significant differences ($p<0.05$)

DISCUSSION

The higher biosecurity scores observed in intensive systems across all dimensions (conceptual, structural, and operational) indicate more consistent implementation of key measures, including farm access control, housing sanitation, animal health management, and waste and carcass disposal. This pattern can be explained by the economic logic of large-scale production: intensive farmers face substantially higher potential losses from disease outbreaks, which creates stronger incentives to adopt stricter and more systematic biosecurity practices. In contrast, smallholders in traditional systems, although generally aware of disease risks, are often constrained by limited financial and material resources, which restrict their ability to implement comparable measures. Semi-intensive and extensive systems further face inherent structural limitations, such as open production environments and limited control over the movement of animals, people, and disease vectors [26,27].

From a structural perspective, confinement in intensive systems reduces both intra-herd and external contact, thereby lowering exposure pathways. While confinement alone cannot fully prevent pathogen introduction, it represents a foundational component of external biosecurity by establishing physical barriers against disease entry [18]. The absence of such barriers in traditional systems substantially increases transmission risk [28]. Notably, the present study found no significant difference in biosecurity scores between semi-intensive and extensive systems (p > 0.05), suggesting that partial intensification does not necessarily translate into meaningful biosecurity improvement. Both systems share critical deficiencies—such as inadequate housing, poor sanitation, and uncontrolled movement—that facilitate pathogen invasion. This finding aligns with Ayebare et al. [29], who reported persistently low biosecurity levels and high antimicrobial use in semi-intensive farms. Taken together, these results suggest that while production intensification is positively associated with improved biosecurity, it is not sufficient on its own; without targeted structural investments and management improvements, transitional systems may remain functionally similar to extensive systems in terms of disease risk.

The particularly low biosecurity scores observed in extensive systems likely reflect minimal investment in infrastructure and weak enforcement of access control. In many cases, pig farming functions as a supplementary livelihood activity or is integrated with other livestock enterprises, which reduces the perceived urgency of biosecurity adoption [30,31]. This perception is compounded by limited technical knowledge, especially in remote areas such as Rindi and Haharu, where access to extension services, information, and financial support remains constrained [29,32]. These findings highlight that low adoption is not solely a matter of awareness, but also of structural and informational inequality.

Beyond technical and economic constraints, biosecurity adoption is also shaped by behavioural and social dynamics. Farmers' motivation to implement biosecurity measures varies considerably, leading to uneven adoption and, in some cases, perceptions of unequal burden among community members [7]. This introduces a collective action problem, in which the effectiveness of biosecurity depends on coordinated behaviour, yet individual farmers bear the costs. In the local context of Sumba, reported practices such as the consumption or sale of meat from infected pigs and improper carcass disposal further exacerbate this challenge by increasing the risk of rapid disease spread. These dynamics underscore a fundamental tension between the collective benefits of biosecurity and the individual incentives faced by smallholders, suggesting that purely technical interventions may be insufficient without addressing underlying social and behavioural factors.

From a policy perspective, the findings indicate that improving biosecurity is less about expanding production scale and more about enabling structural and managerial transformation. While intensification is associated with better outcomes, it should not be interpreted as a universal solution, as its feasibility depends on local resource availability and production contexts. Instead, interventions should prioritize semi-intensive and extensive systems, where the largest gaps persist. Targeted support is needed to strengthen structural biosecurity, including phased investments in fencing, controlled access points, and sanitation infrastructure [33]. For resource-limited farmers, prioritizing low-cost, high-impact measures—such as basic entry restrictions, designated cleaning areas, and improved waste handling—may offer a more feasible entry point than full system intensification [34].

Equally important is the need to tailor interventions to the heterogeneity of smallholder systems. Recognizing variation in resource endowment is critical for designing context-appropriate biosecurity strategies. Strengthening farmer knowledge and awareness should therefore be accompanied by delivery approaches that enable contextual adaptation. Evidence suggests that personalized communication and participatory learning—facilitated by extension agents and veterinarians—are more effective than uniform, top-down approaches in increasing adoption of both internal and external biosecurity measures [28]. Such approaches can help bridge the gap between knowledge and practice by aligning recommendations with farmers' actual constraints and incentives.

Nevertheless, several limitations should be considered when interpreting these findings. First, the study was conducted in the absence of major infectious disease outbreaks, which may have reduced farmers' perceived risk and, consequently, their level of biosecurity compliance. Second, the cross-sectional design limits the ability to assess the consistency of biosecurity implementation over time or to establish causal relationships. Longitudinal studies are therefore needed to better capture the dynamic relationship between biosecurity practices and disease occurrence [35]. Finally, further qualitative research is essential to better understand the socio-economic, behavioural, and technical constraints faced by farmers in semi-intensive and extensive systems, thereby supporting the development of more targeted and context-sensitive policy interventions.

CONCLUSION

This study shows that biosecurity implementation differs significantly across production systems, with intensive systems achieving the highest scores across conceptual, structural, and operational dimensions. Semi-intensive and extensive systems exhibit similarly low biosecurity levels, indicating that partial intensification does not necessarily improve biosecurity performance. These findings indicate that biosecurity in smallholder systems is constrained by limited infrastructure, resources, and implementation capacity. Therefore, improving biosecurity requires targeted efforts to strengthen structural measures and enhance farmer capacity, particularly in semi-intensive and extensive systems.

CONFLICT OF INTEREST

The authors declare no conflict of interest with any financial organization regarding the material discussed in the manuscript. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

ACKNOWLEDGMENTS

This study was funded by the Ministry of Higher Education, Science and Technology (Kemendiktisaintek). The authors gratefully acknowledge Wira Wacana Christian University for facilitating the author's participation in the funding program. Sincere appreciation is extended to Asnad Enunikedo Dawi, Eldion Njurumay, Ridwan Maramba Meha, Tirta Saputra Kale Leo, and Riski Ude George for their valuable assistance during data collection. Lastly, the authors would like to thank Arini Aha Pekuwali and Tri Sari DNB Mira for their scientific support.

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