Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Latent dimensional structure and typology of pig farm biosecurity using Biocheck.UGent™: a multivariate analytical study

Oluwawemimo Adebowale

adebowaleoluwawemimo1@gmail.com

Department of Veterinary Public Health and Preventive Medicine, College of Veterinary Medicine, Federal University of Agriculture, Abeokuta, Nigeria

Abdullah Adeyemi Akinbowale

Department of Veterinary Public Health and Preventive Medicine, College of Veterinary Medicine, Federal University of Agriculture, Abeokuta, Nigeria

Aminu Shittu

Department of Veterinary Public Health and Preventive Medicine, Faculty of Veterinary Medicine, Usmanu Danfodiyo University, Sokoto, Nigeria

Ayomikun Awoseyi

Department of Computer Sciences, Abiola Ajimobi Technical University, Ibadan, Nigeria

Joshua Onyango

The Harper and Keele Veterinary School, Harper Adams University, Edgmond, Newport TF10 8NB and Keele University, Keele, Stafford, ST5 5BG, United Kingdom.

Oladotun Oladipo Oladejo

Department of Veterinary Public Health and Preventive Medicine, College of Veterinary Medicine, Federal University of Agriculture, Abeokuta, Nigeria

Victor Olorunda Malumi

Department of Veterinary Public Health and Preventive Medicine, College of Veterinary Medicine, Federal University of Agriculture, Abeokuta, Nigeria

Godspower Udoudo Nelson

Department of Animal Physiology, College of Animal Science, Federal University of Agriculture, Abeokuta, Nigeria

Folorunsho Elisha Oluwagbeminiyi

Department of Animal Physiology, College of Animal Science, Federal University of Agriculture, Abeokuta, Nigeria

Iryna Makovska

Veterinary Epidemiology Unit, Faculty of Veterinary Medicine, Ghent University, Salisburylaan 133, 9820 Merelbeke, Belgium

Folorunso Oludayo Fasina

daydupe2003@yahoo.co.uk

Department of Agriculture and Animal Health, College of Agriculture and Environmental Sciences, University of South Africa (UNISA), Florida Science Campus, Johannesburg, South Africa.

Research Article

Keywords: Biosecurity, Biocheck.UGent™, Pig production, Principal component analysis, Cluster analysis, Structural equation modeling, Farm typology, Nigeria

Posted Date: July 22nd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10389879/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: The authors declare no competing interests.

Abstract

Understanding the multidimensional structure and classification of farm biosecurity is essential for designing targeted and effective disease prevention strategies. This study aimed to characterize biosecurity performance among commercial pig farms using the Biocheck.UGent™ scoring system and to evaluate its latent dimensional structure, internal consistency, and typological classification. A cross-sectional study was conducted among 76 commercial pig farms in Ogun State, Nigeria. External, internal, and overall biosecurity scores were obtained using the Biocheck.UGent™ tool. Descriptive and reliability analyses were performed, followed by principal component analysis (PCA) and Hierarchical cluster analysis (HCA), which was validated using linear discriminant analysis, multinomial logistic regression, and random forest modeling. Structural equation modeling (SEM) was used to evaluate latent biosecurity constructs and their relationship with overall biosecurity performance. Mean external, internal, and overall biosecurity scores were 48.37 ± 14.39, 65.92 ± 13.20, and 57.34 ± 11.26, respectively, indicating substantially weaker external biosecurity implementation. External biosecurity domains demonstrated moderate internal consistency (Cronbach's α = 0.65). PCA identified two latent dimensions explaining 58.8% of the total variance. Hierarchical clustering identified four distinct biosecurity typologies, which were validated with high classification accuracy using linear discriminant analysis (94.7%) and multinomial regression (100%). Random forest modeling confirmed transportation, animal introduction, and visitor biosecurity as key determinants of typology. SEM demonstrated that external biosecurity represented a significant latent construct and was a strong predictor of overall biosecurity performance (standardized effect = 1.201, $p < 0.001$). Biosecurity implementation in commercial pig farms is a multidimensional construct characterized by distinct and reproducible typological patterns. External biosecurity, particularly animal introduction and transportation practices, represents the primary determinant of overall biosecurity performance. These findings highlight the importance of targeted, domain-specific interventions and demonstrate the value of multivariate structural modeling for improving biosecurity surveillance and disease prevention strategies in pig production systems.

1. Introduction

Biosecurity is widely recognized as the cornerstone of infectious disease prevention in modern pig production systems, serving as the primary barrier against pathogen introduction, amplification, and transmission within and between farms [1–3]. Pig production systems are particularly vulnerable to infectious diseases due to high stocking densities, frequent animal movements, and complex interactions between farms, personnel, and supply chains [4, 5]. Pathogens such as African swine fever virus, porcine reproductive and respiratory syndrome virus (PRRSV), classical swine fever virus, and *Salmonella* spp. continue to pose significant threats to global pig health, food security, and public health [6, 7].

Effective biosecurity practices reduce the likelihood of disease introduction (external biosecurity) and limit within-farm transmission (internal biosecurity), thereby improving animal health, productivity, and economic sustainability [3, 8]. Poor biosecurity has been consistently associated with increased disease

incidence, production losses, reduced reproductive performance, and increased antimicrobial use, which contributes to antimicrobial resistance (AMR) development [9–12]. Conversely, farms with higher biosecurity scores have demonstrated improved health outcomes, reduced mortality, and enhanced economic performance [3, 13, 14]. The economic and epidemiological consequences of inadequate biosecurity are particularly severe in low- and middle-income countries, where pig production systems are expanding rapidly but often operate with limited regulatory oversight and variable implementation of disease prevention measures [15, 16].

In sub-Saharan Africa, including Nigeria, biosecurity implementation remains heterogeneous, increasing vulnerability to transboundary animal diseases such as African swine fever, which has caused substantial economic losses and threatens livelihood security [17–19]. Therefore, robust and objective assessment of farm-level biosecurity is essential for identifying vulnerabilities and designing targeted disease prevention strategies.

To facilitate objective and standardized evaluation of farm biosecurity, several quantitative assessment tools have been developed, among which the Biocheck.UGent™ risk-based scoring system has emerged as one of the most widely validated and internationally applied instruments [1, 2, 20–22]. Developed by Ghent University, Biocheck.UGent™ provides a structured and quantitative evaluation of biosecurity practices based on standardized questionnaires and weighted scoring algorithms. The Biocheck.UGent™ system distinguishes between external and internal biosecurity components. External biosecurity refers to measures designed to prevent pathogen introduction onto farms, including animal introduction protocols, visitor control, transport hygiene, feed and equipment management, and farm location factors. Internal biosecurity encompasses measures that limit pathogen spread within farms, such as compartmentalization, hygiene practices, cleaning and disinfection, and management of different production stages [1, 2, 23]. The system evaluates biosecurity across multiple domains, each scored on a standardized scale from 0 to 100, allowing both domain-specific and composite biosecurity assessment. Biocheck.UGent™ has been applied globally to evaluate biosecurity in diverse production systems and has demonstrated strong utility in identifying biosecurity weaknesses and guiding intervention strategies [2, 20, 24].

Although widespread application of biosecurity scoring tools have been implemented in Nigeria, most published studies rely primarily on descriptive analyses, reporting average biosecurity scores without examining the underlying structural relationships among domains [2, 3]. Such descriptive approaches provide limited insight into the latent structure of biosecurity implementation and fail to determine whether individual biosecurity domains represent a unified construct or multiple independent dimensions.

Furthermore, traditional analyses rarely attempt to classify farms into biosecurity typologies based on shared characteristics. Farm typology classification is essential for identifying distinct subgroups of farms with similar biosecurity profiles, which can facilitate targeted intervention strategies and improve

epidemiological risk management [25–28]. Without such classification, important structural patterns and risk gradients may remain undetected.

Additionally, previous biosecurity studies have seldom employed advanced multivariate techniques such as principal component analysis, cluster analysis, discriminant analysis, or structural equation modeling to evaluate dimensionality, structural relationships, and construct validity. These methods provide powerful tools for identifying latent constructs, validating composite indices, and understanding the multidimensional nature of complex systems such as farm biosecurity [29–32]. Consequently, the structural validity and typological classification of farm biosecurity remain insufficiently explored, particularly in low- and middle-income settings. Given these methodological gaps, the present study aimed to characterized external, internal, and overall biosecurity scores among commercial pig farms and evaluate the internal consistency and reliability of biosecurity domains.

2. Materials and Methods

2.1 Study Design and Farm Population

This study employed a cross-sectional design to assess biosecurity practices among commercial pig farms in Ogun State, Nigeria. A total of 76 (77.5%) out of 98 registered commercial pig farms were included in the analysis. Farms were distributed across multiple administrative areas within the state. Participation was voluntary, and data were collected through structured interviews conducted with farm owners or managers.

2.2 Biosecurity Assessment Tool

Biosecurity practices were assessed using the Biocheck.UGent™ pigs risk-based scoring system, a standardized and internationally validated tool designed to quantify on-farm biosecurity measures. The instrument comprises 12 domains grouped into external and internal biosecurity categories, with each scored on a standardized scale from 0 (lowest level of biosecurity compliance) to 100 (highest level of compliance).

External biosecurity consisted of six subcategories reflecting major pathways of pathogen introduction:

1. Purchase of breeding pigs, weaned piglets and semen
2. Transportation of animals, removal of deadstock and manure
3. Feed, water and equipment supply
4. Visitors and farm workers
5. Vermin and bird control
6. Location of the farm

Each subcategory score was automatically calculated by the Biocheck.UGent™ system based on farmer responses to structured questionnaire items. The external biosecurity subtotal score (SUBT-EBS) represents the aggregated standardized score across subcategories A–F.

Internal biosecurity consisted of six additional subcategories (G–L) assessing disease management and within-farm transmission control measures.

A detailed description of variables, measurement scales, and subcategories classifications is provided in Supplementary Table S1.

2.3 Data Management

Data were exported directly from the Biocheck.UGent™ system into statistical software for analysis. Data cleaning procedures included verification of variable types, detection of out-of-range values, and assessment of missingness across subcategories. Subcategory scores were treated as continuous variables. Where applicable, composite variables were generated, including the external biosecurity subtotal score (SUBT-EBS), internal biosecurity subtotal score, and overall biosecurity score.

Handling of missing subcategories values was addressed through complete-case approaches or sensitivity analyses, depending on the analytical model employed (Table 1). It should be noted that internal biosecurity subcategories did not apply to all farms due to operational differences (Table 1), for instance, three internal biosecurity domains exhibited reduced sample sizes: the farrowing and suckling period subcategory (n = 73), nursery unit subcategory (n = 59), and finishing unit subcategory (n = 35).

This missingness pattern reflects the structural diversity of pig production systems in the study population. Not all commercial pig farms operate farrow-to-finish systems; some specialize in specific production stages such as nursery-only or finishing-only operations. Consequently, while the Biocheck.UGent™ tool assesses all domains comprehensively, certain subcategories are only relevant to farms that actually perform those specific activities. Farms without farrowing facilities, for instance, cannot provide meaningful data for the farrowing period management domain.

To address this incomplete data structure, the analytical approach employed complete-case methods for models requiring full subcategory data, supplemented by sensitivity analyses to assess whether missing data patterns influenced the robustness of identified latent structures and farm typologies. Notably, all external biosecurity domains (A–F) maintained complete data across all 76 farms, as these measures apply universally regardless of farm specialization. The concentration of missing data within production-stage-specific internal biosecurity measures reinforces that these gaps represent genuine structural farm differences rather than data quality issues, and the analytical strategy appropriately accounted for this heterogeneity.

2.4. Statistical Analysis Framework

All statistical analyses were conducted using a structured multi-stage analytical framework designed to comprehensively evaluate the distributional properties, internal consistency, latent dimensional structure, typological classification, structural relationships, and geographic determinants of biosecurity performance among pig farms. This integrative analytical approach allowed both descriptive

characterization and advanced multivariate modeling of biosecurity constructs, thereby providing robust epidemiological and structural insights into farm-level biosecurity implementation.

Prior to multinomial logistic regression and machine learning classification, multicollinearity among predictor variables (external biosecurity domains) was assessed using Variance Inflation Factor (VIF). VIF quantifies the extent to which the variance of a regression coefficient is inflated due to correlation among predictors. Values exceeding 10 indicate problematic multicollinearity, while values below 5 are generally considered acceptable. VIF was calculated using the *vif ()* function from the *car* package in R, with each external biosecurity domain regressed against the remaining domains. This diagnostic ensured that the predictor variables contributed independent information to the classification models and that regression coefficient estimates were stable and interpretable.

2.4.1. Descriptive and Distributional Analysis

Descriptive statistics were computed to summarize external biosecurity scores (EBS), internal biosecurity scores (IBS), and overall biosecurity scores. Measures of central tendency and dispersion included mean, standard deviation (SD), median, interquartile range (IQR), minimum, maximum, and selected percentiles (5th, 25th, 75th, and 95th percentiles) [33]. Comprehensive details of all analyses and formulae are available in Supplementary methods.

Briefly described Descriptive statistics (mean, SD, median, IQR, percentiles) summarized biosecurity scores. Distribution shape was assessed via skewness, kurtosis, and normality tests (Shapiro-Wilk, Q-Q plots). Pearson's correlation quantified linear associations among domains.

Reliability was evaluated using Cronbach's alpha and item-total correlations. Principal component analysis (varimax rotation) identified latent dimensions, retaining eigenvalues > 1 confirmed by scree plots. Hierarchical clustering (Ward's method, Euclidean distance) classified farm typologies. Validation employed linear discriminant analysis (classification accuracy, Box's M), multinomial logistic regression (AIC), and structural equation modeling (CFI, RMSEA, SRMR). Cluster robustness was confirmed via Adjusted Rand Index, and geographic effects via linear regression. Analyses used R 4.3.2 (packages: psych, FactoMineR, MASS, lavaan, cluster, mclust, car, ggplot2). Detailed formulas are in Supplementary methods [30.31,34–41].

All statistical analyses were conducted using R version 4.3.2 (R Foundation for Statistical Computing, Vienna, Austria). Additional statistical validation procedures were performed using psych, FactoMineR, MASS, lavaan, cluster, mclust, car, and ggplot2 packages.

2.4.11. Ethical Approval

Ethical approval

for Livestock (monogastric) Biosecurity studies was obtained from the College of Veterinary Medicine Research Ethics Committee (CREC) at the Federal University of Agriculture, Abeokuta, Ogun State

(FUNAAB), Nigeria, with reference number FUNAAB/COLVET/CREC/2024/03/01. For the human participants, the research was performed in accordance with the Declaration of Helsinki. All farm owners provided informed consent prior to participation.

3. Results

Descriptive Characteristics of Farm Biosecurity

A total of 76 pig farms were assessed using the Biocheck.UGent™ scoring system. The mean EBS was 48.37 ± 14.39, substantially lower than the IBS of 65.92 ± 13.20 (Table 1; Figs. 1a&b). Subcategory-level analysis revealed the highest scores for farrowing period management (74.84 ± 18.46) and cleaning/disinfection (72.75 ± 21.58), while visitor management (42.72 ± 22.36) and feed/water supply (43.62 ± 16.24) showed the greatest weaknesses. External and internal biosecurity were moderately correlated ($r = 0.34$, $p = 0.003$), indicating related but distinct constructs. Detailed distributional characteristics are provided in Fig. 1b and Supplementary Tables S1–S4 and Supplementary Figures S1–S2.

Table 1
Mean biosecurity scores for overall, external, internal, and individual biosecurity subcategories across 76 pig farms assessed using the Biocheck.UGent™ system

Biosecurity Category	No. of farms (n)	Mean	Standard deviation	Minimum	Maximum
External biosecurity score (EBS)	76	48.37	14.39	22	85
Internal biosecurity score (IBS)	76	65.92	13.2	30	92
Overall biosecurity score (EBS + IBS)	76	57.34	11.26	26	81
A. Purchase of breeding pigs, weaned piglets and semen	76	55.34	26.73	11	92
B. Transport of animals, deadstock and manure	76	44.66	17.68	8	84
C. Feed, water and equipment supply	76	43.62	16.24	12	100
D. Visitors and farmworkers	76	42.72	22.36	0	100
E. Vermin and bird control	76	54.38	27.12	5	100
F. Location of the farm	76	49.76	27.34	5	100
G. Disease management	76	48.84	27.92	0	89
H. Farrowing and suckling period	73	74.84	18.46	23	100
I. Nursery unit	59	57.85	23.43	7	86
J. Finishing unit	35	55.69	29.68	8	100
K. Measures between compartments, working lines and use of equipment	76	67.54	27.43	10	100
L. Cleaning and disinfection	76	72.75	21.58	0	100
System score (fc_sys_score)*	76	0	0	0	0

**The "System score (fc_sys_score)" is an internal or technical variable generated by the Biocheck.UGent™ platform. Unlike the External, Internal, and Overall biosecurity scores, which are composite measures derived from farm management practices, this specific variable is a placeholder or an administrative field used by the system's backend.*

Reliability and Dimensionality of External Biosecurity

External biosecurity subcategories demonstrated moderate internal consistency (Cronbach's α = 0.65), suggesting acceptable but not high construct coherence (Supplementary Table S5). Removal of transportation biosecurity substantially reduced alpha (to 0.53), indicating its central role in defining

external biosecurity variation across farms. In contrast, feed and equipment supply showed weaker integration with the overall construct (corrected item-total correlation = 0.21). These findings suggest that external biosecurity is not strictly unidimensional, supporting subsequent dimensionality assessment.

Principal component analysis revealed two latent dimensions with eigenvalues > 1, explaining 58.8% of total variance in external biosecurity subcategories (Table 2, Fig. 1). The first component (PC1; 39.6% variance) was strongly defined by transportation biosecurity (loading = 0.84) and visitor management (0.74), representing a broad external contact and movement control dimension. The second component (PC2; 19.2% variance) was primarily driven by feed/water/equipment supply (loading = 0.78), indicating a resource and environmental biosecurity dimension. Full component loadings are provided in Supplementary Table S6.

Table 2
Principal Component Analysis (PCA) – Eigenvalues and Variance Explained for External Biosecurity subcategories (n = 76 farms)

Principal Component	Eigenvalue	% Variance Explained	Cumulative % Variance
Component 1	2.375	39.59	39.59
Component 2	1.152	19.21	58.79
Component 3	0.993	16.55	75.34
Component 4	0.66	11	86.35
Component 5	0.469	7.81	94.16
Component 6	0.351	5.84	100

Footnote: Comparison of external and internal biosecurity scores across 76 commercial pig farms. The box plots display the distribution of External Biosecurity Score (EBS) and Internal Biosecurity Score (IBS), each measured on a 0–100 scale. External biosecurity scores (mean = 48.37) were substantially lower than internal biosecurity scores (mean = 65.92), indicating that pathogen introduction pathways represent the primary vulnerability in these production systems. The wider interquartile range for external scores (37.5–56.5) compared to internal scores (59.5–73.5) suggests greater variability in implementation of external measures. Whiskers extend to minimum and maximum values, with individual points representing farms with extreme scores. The higher internal scores across all quartiles indicate that once pathogens enter farms, producers implement relatively stronger within-farm hygiene and management practices to limit spread. However, prevention of pathogen introduction through external measures remains the critical weakness requiring targeted intervention. Color bands on y-axis (0–50: red; 50–75: yellow; 75–100: green) provide visual reference for performance categories: poor, moderate, and good biosecurity respectively.

Farm Biosecurity Typologies

Hierarchical clustering of PCA scores identified four distinct biosecurity typologies (Table 3, Figs. 2 and 3). Cluster 1 (25% of farms) exhibited consistently high biosecurity across all external subcategories. Cluster 2 (31.6%) showed moderate biosecurity with specific weaknesses in transportation and visitor management. Cluster 3 (32.9%) demonstrated low scores in animal introduction and visitor control. Cluster 4 (10.5%) had poor feed/water biosecurity but strong vermin control. Individual farm cluster assignments are provided in Supplementary Table S7. Sensitivity analyses confirmed cluster robustness, with high agreement across alternative clustering methods (Adjusted Rand Index = 0.85 for direct clustering; Supplementary Table S8).

Table 3
Distribution of Farms Across Hierarchical Clusters (Ward's Method) (n = 76)

Cluster	Number of Farms	Percentage (%)
1	19	25
2	24	31.6
3	25	32.9
4	8	10.5
Total	76	100

Footnote: Distribution of biosecurity scores across farm categories. Box plots show median (center line), interquartile range (box bounds from Q1 to Q3), and minimum-maximum whiskers for each category. The "Category" axis represents cumulative biosecurity domain combinations, where each "COO" denotes an additional biosecurity component implemented. Categories are ordered hierarchically from single-component implementation (COO) at top to multi-component combinations (COO + COO...+COJ) at bottom, with corresponding Maximum, Q3, Median, Q1, and Minimum values displayed in the adjacent table. Higher maximum scores (16.0 in single-component category) gradually decrease to 0.0 in the most complex multi-component category, suggesting that farms implementing more comprehensive biosecurity portfolios achieve more consistent, moderate scores rather than extreme high or low values. This pattern indicates that biosecurity comprehensiveness is associated with reduced variability and greater standardization of practices.

Footnote: Principal component analysis (PCA) biplot showing farm distribution across the first two dimensions (Dim1 and Dim2), each explaining 20% of total variance. Points represent individual farms colored by cluster membership (clusters 1–4). The spatial distribution demonstrates separation among the four biosecurity typologies identified through hierarchical clustering. Farms in cluster 1 (purple) occupy the positive Dim1 and Dim2 space, indicating higher biosecurity scores across multiple domains. Clusters 2 (green) and 3 (blue) show intermediate positions, while cluster 4 (yellow) clusters separately, reflecting distinct biosecurity profiles. The 20% variance explained by each dimension suggests moderate dimensionality reduction, with remaining variance distributed across additional components. Ellipses

represent 95% confidence intervals for each cluster, confirming statistically meaningful separation between typologies. This visualization validates that the four biosecurity clusters represent genuine structural groupings rather than arbitrary divisions.

Validation of Cluster-Derived Typologies

Linear discriminant analysis confirmed robust separation among clusters, with 94.7% of farms correctly classified (Table 4, Fig. 4). The first discriminant function explained 58.1% of between-cluster variance and was primarily driven by transportation and visitor biosecurity. Cluster 1 farms demonstrated consistently high biosecurity across all domains (e.g., animal introduction: 73.5; visitor management: 65.1). In contrast, Cluster 2 showed pronounced weaknesses in transportation (37.8) and farm location (27.9), while Cluster 3 exhibited particularly low scores in animal introduction (31.4) and visitor control (26.0). Cluster 4 demonstrated strong vermin control (75.0) but poor feed/water biosecurity (24.8) (Table 4, Panel A). Detailed LDA diagnostics are presented in Supplementary Tables S9–S10.

Table 4
Linear Discriminant Analysis results for classification of farms into biosecurity clusters

Panel A. Mean external biosecurity domain scores by cluster				
Subcategory	**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 4**
Purchase of breeding pigs	73.52	72.16	31.35	43.36
Transportation	65.35	37.84	35.35	36.27
Feed, water, equipment	53.17	34.89	51.83	24.82
Visitors and workers	65.09	32.95	26.04	47.64
Vermin and bird control	69.74	32.63	47	75
Location	73	27.89	51.91	40.45
Panel B. *Variance explained by discriminant functions*				
Discriminant Function		**Proportion of trace**	**Percentage**	
LD1		0.581	58.10%	
LD2		0.283	28.30%	
LD3		0.136	13.60%	
Panel C. *Classification accuracy: Confusion matrix*				
Observed	**Predicted Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 4**
Cluster 1	22	0	1	0
Cluster 2	0	17	2	0
Cluster 3	0	0	23	0
Cluster 4	0	1	0	10
Overall classification performance				
Metric				**Value**
Classification accuracy				94.70%

Multicollinearity among predictors was minimal (VIF range: 1.14–1.60; Table 5). Random forest classification independently confirmed transportation biosecurity, animal introduction practices, and visitor management as the most important determinants of cluster membership (Fig. 5). Multinomial logistic regression achieved perfect in-sample classification (100% accuracy; Supplementary Tables S11–S12), although this likely reflects strong cluster separation rather than model overfitting. These findings provide convergent validation of the structural importance of these subcategories, consistent with PCA and LDA results.

Table 5
Multicollinearity diagnostics for external biosecurity domain predictors used in multinomial logistic regression and machine learning classification (n = 76 farms)

Predictor (External biosecurity domain)	Variance Inflation Factor (VIF)
Transportation of animals, removal of deadstock and manure	1.58
Feed, water and equipment supply	1.14
Visitors and farm workers	1.6
Vermin and bird control	1.34
Location of the farm	1.28

Structural Relationships and Determinants of Biosecurity

Structural equation modeling confirmed external biosecurity as a coherent latent construct with all six subcategories loading significantly ($p < 0.001$; Tables 6–8). The strongest loadings were observed for animal introduction (standardized loading = 0.68), transportation (0.52), and visitor management (0.48). Model fit was moderate (CFI = 0.905; RMSEA = 0.18), suggesting that external biosecurity, while meaningful, is a complex multidimensional construct not fully captured by a single latent factor (Table 6). Critically, latent external biosecurity was a dominant predictor of overall biosecurity performance (standardized effect = 1.20, $p < 0.001$; Table 8, Fig. 6), confirming its central role in farm-level disease prevention. Full SEM output, including residual and latent variances, is provided in Supplementary Tables S13–S14.

Table 6
Structural equation model fit indices for latent external biosecurity construct (n = 76 farms)

Fit Index	Value	Interpretation
Sample size (N)	76	Study population
Estimator	Maximum likelihood (ML)	Standard SEM estimation method
χ^2 (df = 14)	48.61	Significant misfit (common in complex models)
p-value	< 0.001	Indicates imperfect model fit
Comparative Fit Index (CFI)	0.905	Acceptable fit (> 0.90)
Tucker–Lewis Index (TLI)	0.857	Marginal fit
RMSEA	0.18	Poor absolute fit (> 0.10)
90% CI (RMSEA)	0.127–0.237	Indicates model misspecification
p (RMSEA ≤ 0.05)	< 0.001	Rejects close fit hypothesis
SRMR	0.119	Moderate residual error
Akaike Information Criterion (AIC)	4566.633	Model comparison index
Bayesian Information Criterion (BIC)	4615.578	Penalized model fit index
Sample-size adjusted BIC (SABIC)	4549.385	Adjusted model comparison index

Table 7
Factor loadings of external biosecurity domains on latent external biosecurity construct

External biosecurity domain	Unstandardized estimate	Standard error	z-value	p-value	Standardized loading
Purchase of breeding pigs, weaned piglets and semen	1.000 (fixed)	–	–	–	0.675
Transportation of animals, removal of deadstock and manure	0.516	0.088	5.827	< 0.001	0.521
Feed, water and equipment supply	0.391	0.07	5.556	< 0.001	0.434
Visitors and farm workers	0.589	0.104	5.687	< 0.001	0.479
Vermin and bird control	0.592	0.114	5.209	< 0.001	0.397
Location of the farm	0.603	0.117	5.173	< 0.001	0.394

Table 8
Structural regression relationship between latent external biosecurity and total biosecurity score

Dependent variable	Predictor	Estimate	Standard error	z-value	p-value	Standardized estimate
Total biosecurity score	External biosecurity (latent variable)	1.914	0.201	9.501	< 0.001	1.201

Footnote: This path diagram represents the structural equation model examining latent external biosecurity as a second-order construct. Rectangles indicate observed variables (external biosecurity subcategories A-F). The circle represents the latent variable (External Biosecurity). Numbers adjacent to arrows from the latent variable to observed variables are standardized factor loadings, indicating the strength of relationship between each subcategory and the underlying construct (all $p < 0.001$). The arrow from latent external biosecurity to Total Biosecurity Score (rectangle) represents the structural regression path, with the standardized coefficient (1.20, $p < 0.001$) indicating that a one-standard-deviation increase in latent external biosecurity is associated with a 1.20-standard-deviation increase in overall biosecurity performance. This confirms external biosecurity as the dominant determinant of total biosecurity.

Consistent with SEM findings, animal introduction (standardized estimate = 0.49), transportation (0.26), and visitor management (0.24) emerged as the strongest structural contributors to external biosecurity (Table 9). All six domains contributed significantly to the construct (all $p < 0.001$; Supplementary Table S13), although their relative importance varied substantially. Introduction of breeding animals demonstrated the strongest contribution (standardized estimate = 0.494; $p = 7.82 \times 10^{-35}$), indicating that

practices related to sourcing replacement stock represent the primary determinant of external biosecurity variation.

Table 9
Structural Contributions of External Biosecurity Domains to the Latent External Biosecurity Construct (n = 76 farms)

Rank	External biosecurity domain	Unstandardized estimate	Standardized estimate	p-value
1	Purchase of breeding pigs, weaned piglets and semen	0.5309	0.4937	7.82×10^{-35}
2	Transportation of animals, removal of deadstock and manure	0.4107	0.2551	1.85×10^{-15}
3	Visitors and farm workers	0.3098	0.2389	3.64×10^{-16}
4	Feed, water and equipment supply	0.3916	0.2214	1.46×10^{-17}
5	Vermin and bird control	0.1986	0.1859	2.74×10^{-13}
6	Location of the farm	0.187	0.1797	3.73×10^{-13}

Geographic location (administrative area) was not significantly associated with total, external, or internal biosecurity scores (all $p > 0.05$; $R^2 < 0.02$), indicating that biosecurity variation was primarily driven by farm-level management rather than regional factors (Supplementary Tables S15–S16). Construct validity of the composite biosecurity index was confirmed by near-perfect correlation with mean subcategory scores ($r = 0.971$; Fig. 7).

Note that domain also refer to subcategory.

4. Discussion

4.1. Interpretation of Biosecurity Level

This study provides a comprehensive structural and typological evaluation of farm biosecurity using the Biocheck.UGent™ system and advanced multivariate analytical methods. Overall, external biosecurity scores were substantially lower than internal biosecurity scores, indicating that pathogen introduction pathways represent the primary vulnerability in the studied pig production systems. This pattern is consistent with previous studies demonstrating that external biosecurity measures – particularly those related to animal introduction, transport, and visitor control – are more difficult to implement and maintain than internal hygiene measures [1, 2, 42].

External biosecurity is critically important because most infectious diseases are introduced into farms through animal movements, contaminated equipment, vehicles, feed, or human activity [43, 44]. Weaknesses in these pathways significantly increase the risk of introduction of transboundary diseases such as African swine fever and porcine reproductive and respiratory syndrome, which have caused major economic losses globally [4, 28, 45]. The relatively higher internal biosecurity scores observed in this study suggest that once pathogens enter farms, producers may implement basic hygiene and management practices to limit spread. However, prevention of pathogen introduction remains the most effective and economically efficient disease control strategy [1, 2, 13].

The moderate overall biosecurity scores observed in this study are comparable to those reported in similar studies conducted in low- and middle-income countries, where biosecurity implementation is often constrained by limited resources, knowledge gaps, and absence of regulatory enforcement [3, 15, 46]. These findings highlight the need for strengthening preventive biosecurity measures at the farm level.

Addressing these biosecurity gaps requires more than technical recommendations; it demands behavioral and educational interventions. Implementing targeted awareness campaigns and capacity-building training programs for farmers, farm workers, and industry stakeholders is essential to reinforce and sustain robust biosecurity practices. Such programs should emphasize the epidemiological rationale behind specific measures, demonstrate practical implementation strategies, and address common misconceptions about disease transmission. Regular refresher training, peer-learning networks, and participatory extension approaches can help embed biosecurity as a routine management priority rather than a compliance burden. These findings underscore that sustainable biosecurity improvement depends on both structural interventions and human capacity development.

4.2. Meaning of Identified Latent Constructs

Principal component analysis and structural equation modeling demonstrated that external biosecurity represents a multidimensional latent construct composed of several interrelated but distinct operational domains. The identification of two primary latent dimensions suggests that biosecurity implementation does not occur along a single continuum but reflects multiple underlying management processes.

The strongest structural contributions were observed for animal introduction practices, transportation biosecurity, and visitor management. These findings are epidemiologically consistent with the well-established role of animal movement and human activity as primary drivers of infectious disease transmission between farms [4, 41, 47–49]. Animal introduction represents one of the highest-risk events for pathogen introduction, particularly in systems lacking quarantine procedures or health certification protocols [50, 51].

Structural equation modeling further confirmed that external biosecurity was a dominant predictor of overall biosecurity performance. This finding aligns with the conceptual distinctions embedded within the Biocheck.UGent™ system, which categorizes biosecurity into external and internal components [2,

22]. The empirical identification of external biosecurity as a coherent multidimensional construct supports the practical utility of domain-based assessment approaches for characterizing farm-level disease risk. The moderate model fit observed suggests that while external biosecurity represents a coherent latent construct, additional contextual factors – such as farm management, farmer behavior, and resource availability – may also influence biosecurity implementation [31, 52].

Understanding why biosecurity implementation varies substantially among farms is critical for designing effective improvement strategies. Previous research in European contexts has demonstrated that biosecurity gaps are frequently linked to limited training, inadequate awareness of disease transmission risks, and farmers' incomplete understanding of pathogen introduction pathways [2, 3]. Similar dynamics likely operate in the Nigerian context, potentially amplified by structural constraints including differential access to financial resources for biosecurity investments, cultural perceptions of disease risk and responsibility, and environmental factors such as farm location relative to high-risk areas.

The farm typologies identified in this study provide indirect evidence of these underlying drivers. Farms in Cluster 1 (high biosecurity) may represent operations with greater access to information, training, or financial capacity, while those in Clusters 2–4 (moderate to low biosecurity) may face barriers in one or more of these domains. For example, the pronounced weakness in transportation biosecurity observed across multiple clusters suggests systemic challenges related to vehicle movement control, potentially reflecting reliance on shared transport services or difficulty implementing cleaning protocols.

Future research should explicitly investigate the socio-economic, cognitive, and structural determinants of biosecurity adoption, including farmers' risk perceptions, training history, membership in producer associations, access to veterinary services, and financial capacity for infrastructure improvements. Understanding these factors would enable targeted interventions that address not only what farmers should do, but also why they currently cannot or do not implement recommended practices, and what support is needed to enable change.

4.3. Farm Typologies and Epidemiological Implications

Hierarchical cluster analysis identified four distinct farm typologies characterised by different biosecurity profiles. These typologies represent structurally meaningful subgroups of farms with shared biosecurity characteristics, reflecting heterogeneity in disease risk.

The existence of distinct typologies has important epidemiological implications. Farms with consistently low external biosecurity represent high-risk nodes for pathogen introduction and may serve as entry points for disease outbreaks within regional production networks [47]. Conversely, farms with higher biosecurity may function as epidemiological barriers, reducing disease transmission.

The identification of typologies supports the concept that biosecurity improvement strategies should not be uniform but tailored to specific farm profiles [26, 53, 54]. Typology-based approaches enable more efficient allocation of resources and targeted interventions, thereby improving disease prevention effectiveness.

The high classification accuracy observed using discriminant analysis and machine learning methods confirms that these typologies represent robust and biologically meaningful classifications rather than statistical artifacts.

4.4. Comparison with Other Biocheck Studies

The biosecurity scores observed in this study are generally consistent with findings from previous Biocheck.UGent™ studies conducted in Europe, Asia, and Africa, although absolute scores vary depending on production system characteristics and regional context [1, 2, 3].

Similar to the present study, previous research has consistently reported lower external biosecurity scores compared to internal biosecurity scores, highlighting the universal challenge of controlling pathogen introduction pathways [2]. Interestingly, a European study reported that external biosecurity measures were well implemented, although it examined only one subcategory of cleaning and disinfection [55]. Overall, most previous studies have relied primarily on descriptive analysis without evaluating latent structural relationships or farm typologies.

The relatively high cleaning and disinfection score observed in this study (72.75 ± 21.58) is notably higher than those reported in European studies. For instance, Makovska et al. [55], examined cleaning and disinfection practices across ten European countries and found considerable variation, with many farms demonstrating suboptimal implementation of these critical internal biosecurity measures. The higher scores in our study may reflect either genuine strengths in post-cleaning protocols at Nigerian pig farms or differences in the interpretation of assessments. However, it is important to note that high scores in cleaning and disinfection do not necessarily compensate for weaknesses in external biosecurity, as pathogen introduction through animal movements, transportation, and visitor access remains the primary disease risk pathway. This finding underscores the need for balanced biosecurity investments across both external and internal domains.

The moderate positive correlation observed between external and internal biosecurity scores ($r = 0.34$, $p = 0.003$) indicates that farms with stronger external biosecurity tend also to implement better internal biosecurity, but the relationship is far from deterministic. This suggests that these two dimensions of biosecurity are related but distinct constructs, influenced by different management priorities and resource allocations. Some farms may invest heavily in preventing pathogen introduction while neglecting within-farm spread controls, or vice versa. This dissociation has important implications: a farm with excellent external biosecurity but poor internal biosecurity remains vulnerable to disease amplification and transmission once pathogens enter, while a farm with strong internal controls but weak external barriers remains at high risk of initial introduction events. Effective disease prevention requires balanced attention to both dimensions.

The identification of four distinct biosecurity typologies reveals that farms do not simply exist along a single continuum from low to high biosecurity. Instead, they exhibit qualitatively different profiles of strengths and weaknesses. Cluster 1 (25% of farms) represents exemplary biosecurity performance

across all domains and may serve as models for best practice demonstration. Cluster 2 (31.6%) demonstrates moderate overall biosecurity but specific vulnerabilities in transportation and visitor management—two critical external pathways—suggesting targeted interventions could yield substantial improvement. Cluster 3 (32.9%) shows pronounced weaknesses in animal introduction and visitor control, indicating high-risk status for pathogen entry. Cluster 4 (10.5%) presents an unusual profile with excellent vermin control but poor feed/water biosecurity, potentially reflecting farm-specific prioritization based on perceived local risks. These typologies provide a practical framework for risk stratification and tailored extension messaging.

The absence of significant geographic variation in biosecurity scores across administrative areas ($R^2 < 0.02$, all $p > 0.05$) suggests that farm-level management factors, rather than regional characteristics, are the primary determinants of biosecurity implementation. This finding implies that improvement strategies should focus on individual farm engagement and tailored support rather than assuming geographic uniformity in needs or one-size-fits-all regional programs. However, the limited geographic scope of this study (single Nigerian state) may mask regional differences that would emerge at larger scales; multi-state or multi-country studies are needed to fully characterize geographic determinants of biosecurity variation.

The present study extends previous work by incorporating advanced multivariate and structural modeling approaches, providing deeper insight into the multidimensional nature of biosecurity implementation.

4.5. Methodological Strengths

A major strength of this study is the application of a comprehensive multivariate analytical framework integrating principal component analysis, cluster analysis, discriminant analysis, multinomial regression, machine learning, and structural equation modeling. These methods allowed evaluation of both descriptive and structural properties of biosecurity implementation.

The use of multiple independent validation approaches provides strong evidence for the robustness and validity of the identified biosecurity typologies. Machine learning validation further strengthens the reliability of the classification results.

Sensitivity analyses confirmed that the cluster structure remained stable under alternative analytical conditions, supporting the reproducibility of the findings.

Such integrated analytical approaches have rarely been applied in biosecurity research and represent a methodological advancement in the field.

4.6. Limitations

Several limitations should be considered. First, the cross-sectional design limits causal inference. Biosecurity practices and disease risk relationships cannot be interpreted temporally. Second, the sample size, although adequate for multivariate analysis, may limit generalizability to all pig production

systems in Nigeria. Third, missing data in certain internal biosecurity domains reflects structural differences between farms and may influence composite score estimation. Fourth, structural equation modeling demonstrated only moderate model fit, suggesting that additional unmeasured variables may contribute to biosecurity variation.

Despite these limitations, the use of multiple complementary analytical methods strengthens confidence in the study findings.

4.7. Policy and Practice Implications

The findings have important implications for disease prevention policy and farm management.

Targeted interventions focusing on high-risk domains – particularly animal introduction and transportation practices – are likely to produce the greatest improvement in biosecurity performance.

The identification of farm typologies provides a practical framework for designing typology-specific biosecurity improvement programs. Such targeted approaches are more efficient than uniform intervention strategies.

These findings also support the use of structured biosecurity assessment tools and multivariate modeling approaches for surveillance and disease prevention planning.

Strengthening farm-level biosecurity is essential for protecting animal health, improving productivity, and preventing transboundary disease outbreaks.

5. Conclusions

This study demonstrates that farm biosecurity is a multidimensional construct comprising interrelated but distinct operational subcategories, rather than a single uniform measure. The identification of latent biosecurity dimensions confirms that different components reflect underlying structural processes related to pathogen exclusion and within-farm disease control, supporting domain-based assessment approaches.

The classification of farms into four distinct biosecurity typologies reveals stable, reproducible groupings validated across multiple analytical approaches. These typologies represent meaningful differences in disease prevention capacity and provide a practical framework for risk stratification and targeted intervention design.

External biosecurity was identified as the strongest determinant of overall biosecurity performance, emphasizing the critical importance of measures preventing pathogen introduction—particularly animal introduction, transportation, and visitor management. These domains should be priority targets for intervention programs.

The application of multivariate analytical techniques enabled identification of latent constructs, validation of biosecurity classification, and improved understanding of the structural organization of biosecurity practices. Integrating such approaches into biosecurity assessment enhances interpretive value and provides a robust foundation for designing evidence-based disease prevention strategies in pig production systems.

Declarations

Authors' Contributions

O.O. Adebowale; Writing – original draft, Review and Editing, Validation, Methodology, Investigation Formal analysis, Conceptualization, Supervision. A.A. Akinbowale; Writing – original draft, Review and Editing, Validation, Methodology, Investigation Formal analysis, Conceptualization. A. Shittu; Writing – original draft, Review and Editing, Validation, Methodology, Investigation Formal analysis, Conceptualization. A. Awoseyi; Writing – original draft, Review and Editing, Validation, Methodology, Investigation Formal analysis, Conceptualization. J. Onyango; Writing – original draft, Review and Editing, Validation, Methodology, Investigation Formal analysis, Conceptualization. O.O. Oladejo; Writing – original draft, Review and Editing, Validation, Methodology, Investigation Formal analysis, Conceptualization. V.O. Malumi; Writing – original draft, Review and Editing, Validation, Methodology, Investigation Formal analysis, Conceptualization. G.U. Nelson; Writing – original draft, Review and Editing, Validation, Methodology, Investigation Formal analysis, Conceptualization. F.E. Oluwagbeminiyi; Writing – original draft, Review and Editing, Validation, Methodology, Investigation Formal analysis, Conceptualization. I. Makovska; Writing – original draft, Review and Editing, Validation, Methodology, Investigation Formal analysis, Conceptualization. F.O. Fasina; Writing – original draft, Review and Editing, Validation, Methodology, Investigation Formal analysis, Conceptualization

Acknowledgement

We thank Prof. Dr. Jeroen Dewulf of the Faculty of Veterinary Medicine, Ghent University, Belgium for his technical support during this work and for providing the redacted data generated in the Biocheck system for further analyses. We appreciate all the field operators who assisted in data collections. We thank the Pig Farmers' Association, Ogun State Chapter and local authorities who gave permission for the work to be carried out. AI Assistance: Due to the volume of results generated, the AI was used only to reorganise the results into those to fit into the manuscript and those to go into Supplementary materials after the original draft was done by the authors.

Conflict of Interest Disclosure

The authors declare there are no conflicts of interest for this manuscript.

Funding

No, this research did not receive funding.

Data availability

All data generated or analysed during this study are included in this published article (and its Supplementary Information files).

References

1. Laanen M, Persoons D, Ribbens S, de Jong E, Callens B, Strubbe M, Maes D, Dewulf J (2013) Relationship between biosecurity and production/antimicrobial treatment characteristics in pig herds. Vet J 198(2):508–512 Epub 2013 Sep 2. PMID: 24268483
2. Postma M, Backhans A, Collineau L, Loesken S, Sjölund M, Belloc C, Emanuelson U, Grosse Beilage E, Nielsen EO, Stärk KDC, Dewulf J, MINAPIG consortium (2016) 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. Porcine Health Manag 2:9. 10.1186/s40813-016-0028-z. PMID: 28405435; PMCID: PMC5382489
3. Alarcón LV, Allepuz A, Mateu E (2021) Biosecurity in pig farms: a review. Porcine Health Manag. ;7(1):5. doi: 10.1186/s40813-020-00181-z. Erratum in: Porcine Health Manag. 2021;7(1):24. 10.1186/s40813-021-00202-5. PMID: 33397483; PMCID: PMC7780598
4. Costard S, Porphyre V, Messad S, Rakotondrahanta S, Vidon H, Roger F, Pfeiffer DU (2009) Multivariate analysis of management and biosecurity practices in smallholder pig farms in Madagascar. Prev Vet Med 92(3):199–209. 10.1016/j.prevetmed.2009.08.010. Epub 2009 Sep 24. PMID: 19781801; PMCID: PMC2806948
5. Haile B, Liu C, Carrai M, Go YY, Yip CK, Ng LT, Au Yeung YG, Luk KY, Havas KA, Ivanek R, Pfeiffer DU, Conan A, Nekouei O (2025) Characterization of biosecurity practices and viral infections on pig farms in Hong Kong. Prev Vet Med 242:106569 Epub 2025 May 14. PMID: 40414194
6. Cochran HJ, Bosco-Lauth AM, Garry FB, Roman-Muniz IN, Martin JN (2023) African Swine Fever: A Review of Current Disease Management Strategies and Risks Associated with Exhibition Swine in the United States. Animals 13(23):3713. https://doi.org/10.3390/ani13233713
7. Kwon T, Bae GS, Jeon E, Kang P, Son HC, An YJ, Koo BS, Kim SU, Lim KS (2025) Jul-Aug;39(4):1810–1832 Global Challenges and Advancements in the Management of Pivotal Porcine/Swine Viral Diseases. In Vivo. 10.21873/invivo.13982. PMID: 40578970; PMCID: PMC12223619
8. Mehmedi B, Iatrou AM, Yildiz R, Lamont K, da Costa MR, De Nardi M, Allepuz A, Niine T, Niemi JK, Saegerman C (2025) Economic Perspectives on Farm Biosecurity: Stakeholder Challenges and Livestock Species Considerations. Agriculture 15(21):2288. https://doi.org/10.3390/agriculture15212288
9. O'Neill L, Calderón Díaz JA, Rodrigues da Costa M, Oakes S, Leonard FC, Manzanilla EG (2021) Risk Factors for Antimicrobial Use on Irish Pig Farms. Animals 11(10):2828. https://doi.org/10.3390/ani11102828

10. Dhaka P, Chantziaras I, Vijay D, Bedi JS, Makovska I, Biebaut E, Dewulf J (2023) Can Improved Farm Biosecurity Reduce the Need for Antimicrobials in Food Animals? Scoping Rev Antibiot (Basel) 12(5):893. 10.3390/antibiotics12050893. PMID: 37237795; PMCID: PMC10215210
11. Jaleta M, Junker V, Kolte B, Börger M, Werner D, Dolsdorf C, Schwenker J, Hölzel C, Zentek J, Amon T, Nübel U, Kabelitz T (2024) Improvements of weaned pigs barn hygiene to reduce the spread of antimicrobial resistance. Front Microbiol 15:1393923 PMID: 38812683; PMCID: PMC11135127
12. Mallioris P, Luiken REC, Tobias T, Vonk J, Wagenaar JA, Stegeman A, Mughini-Gras L (2024) Risk factors for antimicrobial use in Dutch pig farms: A cross-sectional study. Res Vet Sci 174:105307. 10.1016/j.rvsc.2024.105307. Epub 2024 May 16. PMID: 38781817
13. Scollo A, Perrucci A, Stella MC, Ferrari P, Robino P, Nebbia P (2023) Biosecurity and Hygiene Procedures in Pig Farms: Effects of a Tailor-Made Approach as Monitored by Environmental Samples. Animals 13(7):1262. https://doi.org/10.3390/ani13071262
14. Shrestha S, da Costa MR, Correia-Gomes C, Nevel A, McGowan A, Tongue SC (2024) An economic assessment of alternative antimicrobial use scenarios on pig farms. Front Veterinary Sci 11:1381499
15. Mutua F, Dione M (2021) The Context of Application of Biosecurity for Control of African Swine Fever in Smallholder Pig Systems: Current Gaps and Recommendations. Front Vet Sci 8:689811. 10.3389/fvets.2021.689811. PMID: 34409087; PMCID: PMC8364973
16. Renault V, Masson A, Xaphokame P, Phommasack O, Sear B, Ven S, Saegerman C (2026) Knowledge, Attitudes, and Biosecurity Practices Regarding African Swine Fever Among Small-Scale Pig Farmers in the Lao People's Democratic Republic and Cambodia. Viruses 18(1):34. https://doi.org/10.3390/v18010034
17. Omowon AA, Daodu OB, Omowon AM, Bello II (2019) Knowledge, attitude and practices of pig farmers post African swine fever outbreaks in Ogun and Oyo states of Nigeria. Sokoto J Veterinary Sci 17(4):14–24
18. Ngom RV, Ayissi GJ, Akoussa AMM, Laconi A, Jajere SM, Zangue HA, Piccirillo A (2024) A Systematic Review and Meta-Analysis of the Efficacy of Biosecurity in Disease Prevention and Control in Livestock Farms in Africa. Transbound Emerg Dis. ; 2024:8683715. 10.1155/2024/8683715. PMID: 40303053; PMCID: PMC12016774
19. Ceruti A, Kobialka RM, Abd El Wahed A, Truyen U (2025) African Swine Fever: A One Health Perspective and Global Challenges. Anim (Basel) 15(7):928. 10.3390/ani15070928. PMID: 40218322; PMCID: PMC11987808
20. Gelaude P, Schlepers M, Verlinden M, Laanen M, Dewulf J (2014) Biocheck. UGent: a quantitative tool to measure biosecurity at broiler farms and the relationship with technical performances and antimicrobial use. Poult Sci 93(11):2740–2751
21. Da Costa MR, Gasa J, Díaz JA, Postma M, Dewulf J, McCutcheon G, Manzanilla EG (2019) Using the Biocheck. UGent™ scoring tool in Irish farrow-to-finish pig farms: assessing biosecurity and its relation to productive performance. Porcine Health Manage 5:4

22. Amalraj A, Van Meirhaeghe H, Caekebeke N, Creve R, Dufay-Lefort AC, Rousset N, Spaans A, Devesa A, Tilli G, Piccirillo A, Żbikowski A, Kovács L, Chantziaras I, Dewulf J (2024) Development and use of Biocheck.UGent™ scoring system to quantify biosecurity in conventional indoor (turkey, duck, breeder) and free-range (layer and broiler) poultry farms. Prev Vet Med 230:106288. 10.1016/j.prevetmed.2024.106288. Epub 2024 Jul 20. PMID: 39067265
23. Ibrahim N, Chantziaras I, Chakma S, Islam SS, Amalraj A, Caekebeke N, de Carvalho Ferreira H, Dewulf J (2025) Biocheck.UGent: A risk-based tool to assess the status of biosecurity in backyard poultry in low- and middle-income countries. Prev Vet Med 241:106540 Epub 2025 May 1. PMID: 40359586
24. Tanquilut NC, Espaldon MVO, Eslava DF, Ancog RC, Medina CDR, Paraso MGV, Domingo RD, Dewulf J (2020) Quantitative assessment of biosecurity in broiler farms using Biocheck.UGent in Central Luzon, Philippines. Poult Sci 99(6):3047–3059. 10.1016/j.psj.2020.02.004. Epub 2020 Mar 5. PMID: 32475441; PMCID: PMC7597688
25. Köbrich C, Rehman T, Khan M (2003) Typification of farming systems for constructing representative farm models: two illustrations of the application of multi-variate analyses in Chile and Pakistan. Agric Syst 76(1):141–157
26. Bergmann H, Dups-Bergmann J, Schulz K, Probst C, Zani L, Fischer M, Gethmann J, Denzin N, Blome S, Conraths FJ, Sauter-Louis C (2022) Identification of Risk Factors for African Swine Fever: A Systematic Review. Viruses 14(10):2107. 10.3390/v14102107. PMID: 36298662; PMCID: PMC9611626
27. Sinha A, Basu D, Priyadarshi P, Ghosh A, Sohane RK (2022) Farm typology for targeting extension interventions among smallholders in tribal villages in Jharkhand state of India. Front Environ Sci 10:823338
28. Otieno WA, Nyikal RA, Mbogoh SG, Rao EJO (2023) Adoption of farm biosecurity practices among smallholder poultry farmers in Kenya - An application of latent class analysis with a multinomial logistic regression. Prev Vet Med 217:105967. 10.1016/j.prevetmed.2023.105967. Epub 2023 Jun 23. PMID: 37406503
29. Worley B, Powers R (2013) Multivariate Analysis in Metabolomics. Curr Metabolomics 1(1):92–107. 10.2174/2213235X11301010092. PMID: 26078916; PMCID: PMC4465187
30. Jolliffe IT, Cadima J (2016) Principal component analysis: a review and recent developments. Philos Trans A Math Phys Eng Sci. ;374(2065):20150202. 10.1098/rsta.2015.0202. PMID: 26953178; PMCID: PMC4792409
31. Kline RB (2016) Principles and practice of structural equation modeling, 4th edn. Guilford Press, New York
32. Wani AA (2025) Comprehensive review of dimensionality reduction algorithms: challenges, limitations, and innovative solutions. PeerJ Comput Sci 11:e3025. 10.7717/peerj-cs.3025. PMID: 40989337; PMCID: PMC12453773
33. Altman DG, Bland JM (2005) Standard deviations and standard errors. BMJ 331(7521):903

34. Ghasemi A, Zahediasl S (2012) Normality tests for statistical analysis: A guide for non-statisticians. Int J Endocrinol Metabolism 10(2):486–489
35. Shapiro SS, Wilk MB (1965) An analysis of variance test for normality (complete samples). Biometrika 52(3/4):591–611
36. Streiner DL (2003) Starting at the beginning: An introduction to coefficient alpha and internal consistency. J Pers Assess 80(1):99–103. https://doi.org/10.1207/S15327752JPA8001_18
37. Cliff N (1988) The eigenvalues-greater-than-one rule and the reliability of components. Psychol Bull 103(2):276
38. D'agostino Sr RB, Russell HK (2005) Scree test. Encyclopedia Biostatistics. ;7
39. Murtagh F, Legendre P (2014) Ward's hierarchical agglomerative clustering method: which algorithms implement Ward's criterion? J Classif 31(3):274–295
40. Kächele F, Schneider N (2025) Cluster Validation Based on Fisher's Linear Discriminant Analysis. J Classif 42(1):54–71
41. Steinley D (2004) Properties of the Hubert-Arabie adjusted Rand index. Psychol Methods. ;9(3):386 – 96. 10.1037/1082-989X.9.3.386. PMID: 15355155
42. Kruse AB, Nielsen LR, Alban L (2020) Herd typologies based on multivariate analysis of biosecurity, productivity, antimicrobial and vaccine use data from Danish sow herds. Prev Vet Med 181:104487. 10.1016/j.prevetmed.2018.06.008. Epub 2018 Jun 22. PMID: 29960650
43. Robertson ID (2020) Disease control, prevention and on-farm biosecurity: the role of veterinary epidemiology. Engineering 6(1):20–25
44. Saxena H, Kumar A, Sarkar VK, Kansal M, Verma K (2025) Strategies of Disease Management: Prevention, Control, and On-farm Biosecurity. Epidemiology and Environmental Hygiene in Veterinary Public Health. 6:145–154
45. Beltran-Alcrudo D, Falco JR, Raizman E, Dietze K (2019) Transboundary spread of pig diseases: the role of international trade and travel. BMC Vet Res 15(1):64. 10.1186/s12917-019-1800-5. PMID: 30795759; PMCID: PMC6387505
46. Pinto Jimenez CE, Keestra S, Tandon P, Cumming O, Pickering AJ, Moodley A, Chandler CIR (2023) Biosecurity and water, sanitation, and hygiene (WASH) interventions in animal agricultural settings for reducing infection burden, antibiotic use, and antibiotic resistance: a One Health systematic review. Lancet Planet Health. ;7(5):e418-e434. 10.1016/S2542-5196(23)00049-9. PMID: 37164518
47. Boklund A, Dhollander S, Chesnoiu Vasile T, Abrahantes JC, Bøtner A, Gogin A, Gonzalez Villeta LC, Gortázar C, More SJ, Papanikolaou A, Roberts H, Stegeman A, Ståhl K, Thulke HH, Viltrop A, Van der Stede Y, Mortensen S (2020) Risk factors for African swine fever incursion in Romanian domestic farms during 2019. Sci Rep 10(1):10215. 10.1038/s41598-020-66381-3. PMID: 32576841; PMCID: PMC7311386
48. Esposito MM, Turku S, Lehrfield L, Shoman A (2023) The Impact of Human Activities on Zoonotic Infection Transmissions. Anim (Basel) 13(10):1646. 10.3390/ani13101646. PMID: 37238075; PMCID: PMC10215220

49. European Food Safety Authority (EFSA), Nielsen SS, Alvarez J, Bicout DJ, Calistri P, Depner K, Drewe JA, Garin-Bastuji B, Gonzales Rojas JL, Schmidt C, Herskin M, Michel V, Pasquali P, Roberts HC, Sihvonen LH, Spoolder H, Stahl K, Velarde A, Winckler C, Blome S, Boklund A, Bøtner A, Dhollander S, Rapagnà C, Van der Stede Y, Miranda Chueca MA (2021) Research objectives to fill knowledge gaps in African swine fever virus survival in the environment and carcasses, which could improve the control of African swine fever virus in wild boar populations. EFSA J 19(6):e06675. 10.2903/j.efsa.2021.6675. PMID: 34188717; PMCID: PMC8215587
50. Craft ME (2015) Infectious disease transmission and contact networks in wildlife and livestock. Philos Trans R Soc Lond B Biol Sci 370(1669):20140107. 10.1098/rstb.2014.0107. PMID: 25870393; PMCID: PMC4410373
51. Gierak A, Śmietanka K (2021) Models To Assess the Risk of Introduction of Selected Animal Viral Diseases Through the Importation of Live Animals As a Key Part of Risk Analysis. J Vet Res 65(4):383–389. 10.2478/jvetres-2021-0069. PMID: 35111990; PMCID: PMC8775722
52. Moura P, Küker S, Farnell M, Stowell-Moss J, Tickel J, Buholzer P, Simmons HL (2025) Socio-Psychological and External Factors Influencing Biosecurity Compliance in U.S. Poultry Farming. Vet Sci 12(10):925. 10.3390/vetsci12100925. PMID: 41150064; PMCID: PMC12567621
53. Fasina FO, Agbaje M, Ajani FL, Talabi OA, Lazarus DD, Gallardo C, Thompson PN, Bastos AD (2012) Risk factors for farm-level African swine fever infection in major pig-producing areas in Nigeria, 1997–2011. Prev Vet Med 107(1–2):65–75 Epub 2012 Jun 19. PMID: 22717326
54. Yona C, Makange MR, Moshiro E, Hakizimana JN, Mfumbilwa ZA, Lupala AS, Chengula AA, Misinzo G (2025) African Swine Fever Perception, Risk Factors, and Socioeconomic Disparities Among Smallholder Domestic Pig Farmers in Serengeti, Tanzania. Transbound Emerg Dis. ; 2025:3922067. 10.1155/tbed/3922067. PMID: 40909123; PMCID: PMC12408130.ss
55. Makovska I, Chantziaras I, Caekebeke N, Dhaka P, Dewulf J (2024) Assessment of Cleaning and Disinfection Practices on Pig Farms across Ten European Countries. Anim (Basel) 14(4):593. 10.3390/ani14040593. PMID: 38396561; PMCID: PMC10886142

Figures

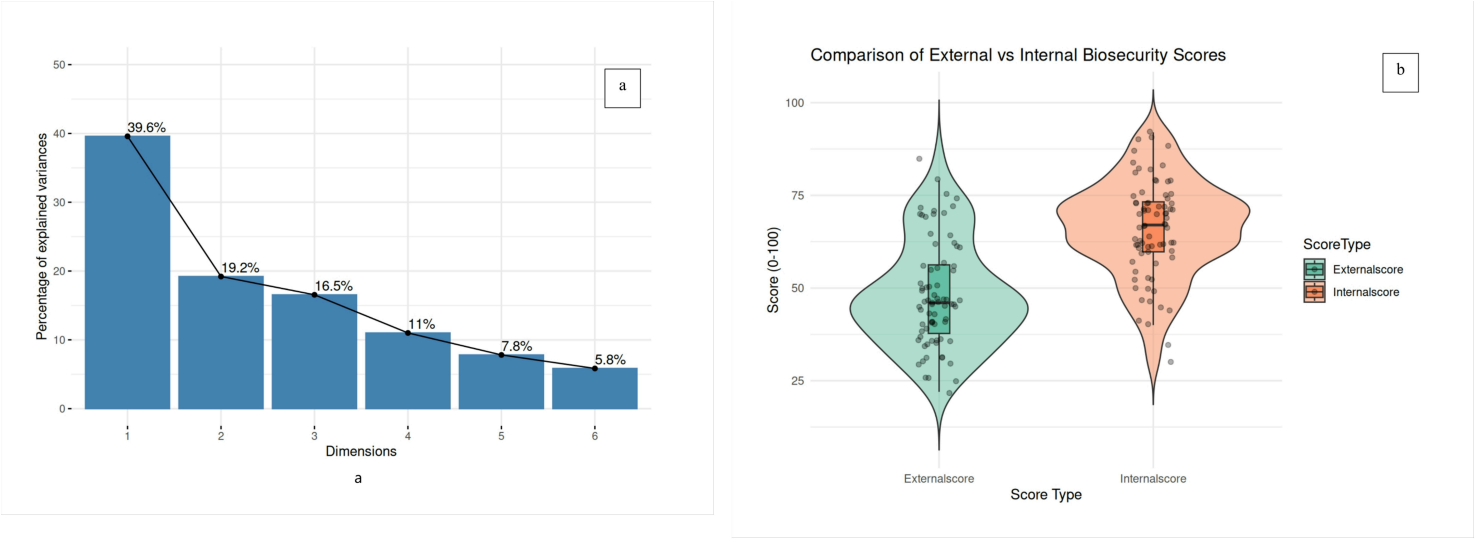


Figure 1

a. Scree Plot of eigenvalues for external biosecurity subcategories; **b.** Violin plot showing distribution of external and internal biosecurity scores among pig farms (n = 76)

Footnote: Comparison of external and internal biosecurity scores across 76 commercial pig farms. The box plots display the distribution of External Biosecurity Score (EBS) and Internal Biosecurity Score (IBS), each measured on a 0–100 scale. External biosecurity scores (mean = 48.37) were substantially lower than internal biosecurity scores (mean = 65.92), indicating that pathogen introduction pathways represent the primary vulnerability in these production systems. The wider interquartile range for external scores (37.5–56.5) compared to internal scores (59.5–73.5) suggests greater variability in implementation of external measures. Whiskers extend to minimum and maximum values, with individual points representing farms with extreme scores. The higher internal scores across all quartiles indicate that once pathogens enter farms, producers implement relatively stronger within-farm hygiene and management practices to limit spread. However, prevention of pathogen introduction through external measures remains the critical weakness requiring targeted intervention. Color bands on y-axis (0–50: red; 50–75: yellow; 75–100: green) provide visual reference for performance categories: poor, moderate, and good biosecurity respectively

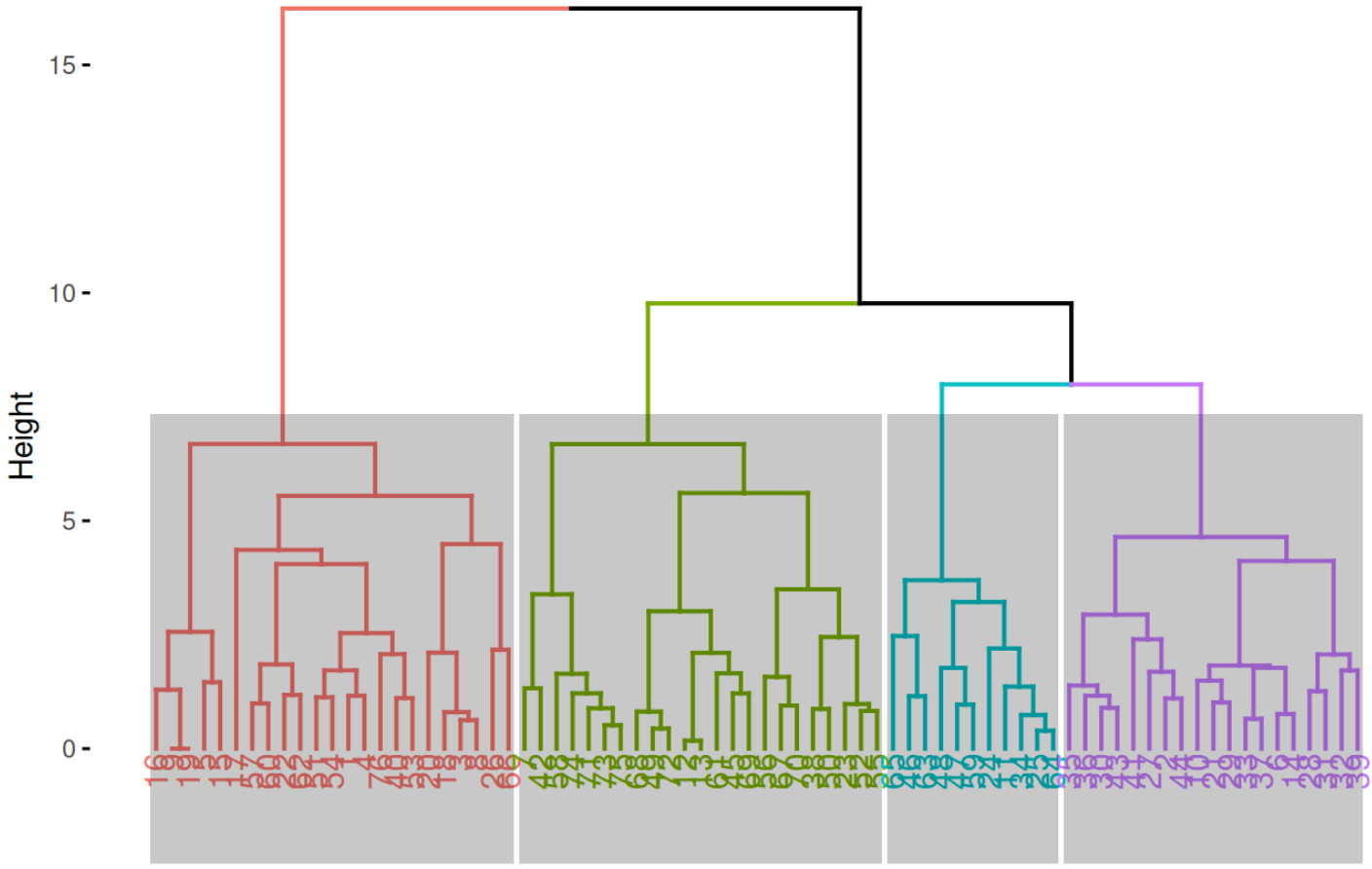


Figure 2

Hierarchical Clustering Dendrogram of Farms Based on PCA Scores (Ward's Method)

Footnote: Distribution of biosecurity scores across farm categories. Box plots show median (center line), interquartile range (box bounds from Q1 to Q3), and minimum-maximum whiskers for each category. The "Category" axis represents cumulative biosecurity domain combinations, where each "COO" denotes an additional biosecurity component implemented. Categories are ordered hierarchically from single-component implementation (COO) at top to multi-component combinations (COO+COO...+COJ) at bottom, with corresponding Maximum, Q3, Median, Q1, and Minimum values displayed in the adjacent table. Higher maximum scores (16.0 in single-component category) gradually decrease to 0.0 in the most complex multi-component category, suggesting that farms implementing more comprehensive biosecurity portfolios achieve more consistent, moderate scores rather than extreme high or low values. This pattern indicates that biosecurity comprehensiveness is associated with reduced variability and greater standardization of practices.

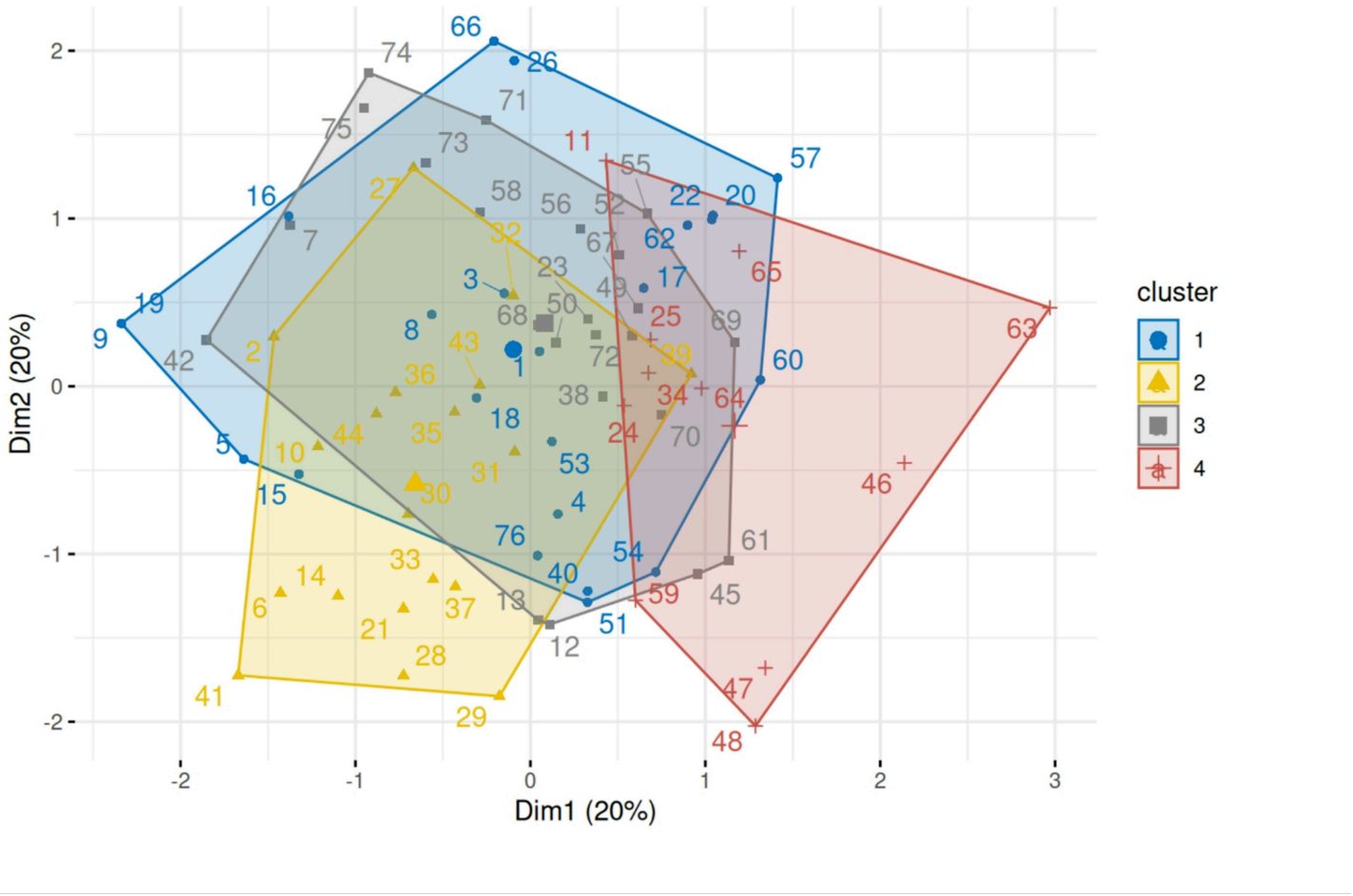


Figure 3

Cluster Plot of Farms in PCA Space (PC1 vs PC2)

Footnote: Principal component analysis (PCA) biplot showing farm distribution across the first two dimensions (Dim1 and Dim2), each explaining 20% of total variance. Points represent individual farms colored by cluster membership (clusters 1-4). The spatial distribution demonstrates separation among the four biosecurity typologies identified through hierarchical clustering. Farms in cluster 1 (purple) occupy the positive Dim1 and Dim2 space, indicating higher biosecurity scores across multiple domains. Clusters 2 (green) and 3 (blue) show intermediate positions, while cluster 4 (yellow) clusters separately, reflecting distinct biosecurity profiles. The 20% variance explained by each dimension suggests moderate dimensionality reduction, with remaining variance distributed across additional components. Ellipses represent 95% confidence intervals for each cluster, confirming statistically meaningful separation between typologies. This visualization validates that the four biosecurity clusters represent genuine structural groupings rather than arbitrary divisions.

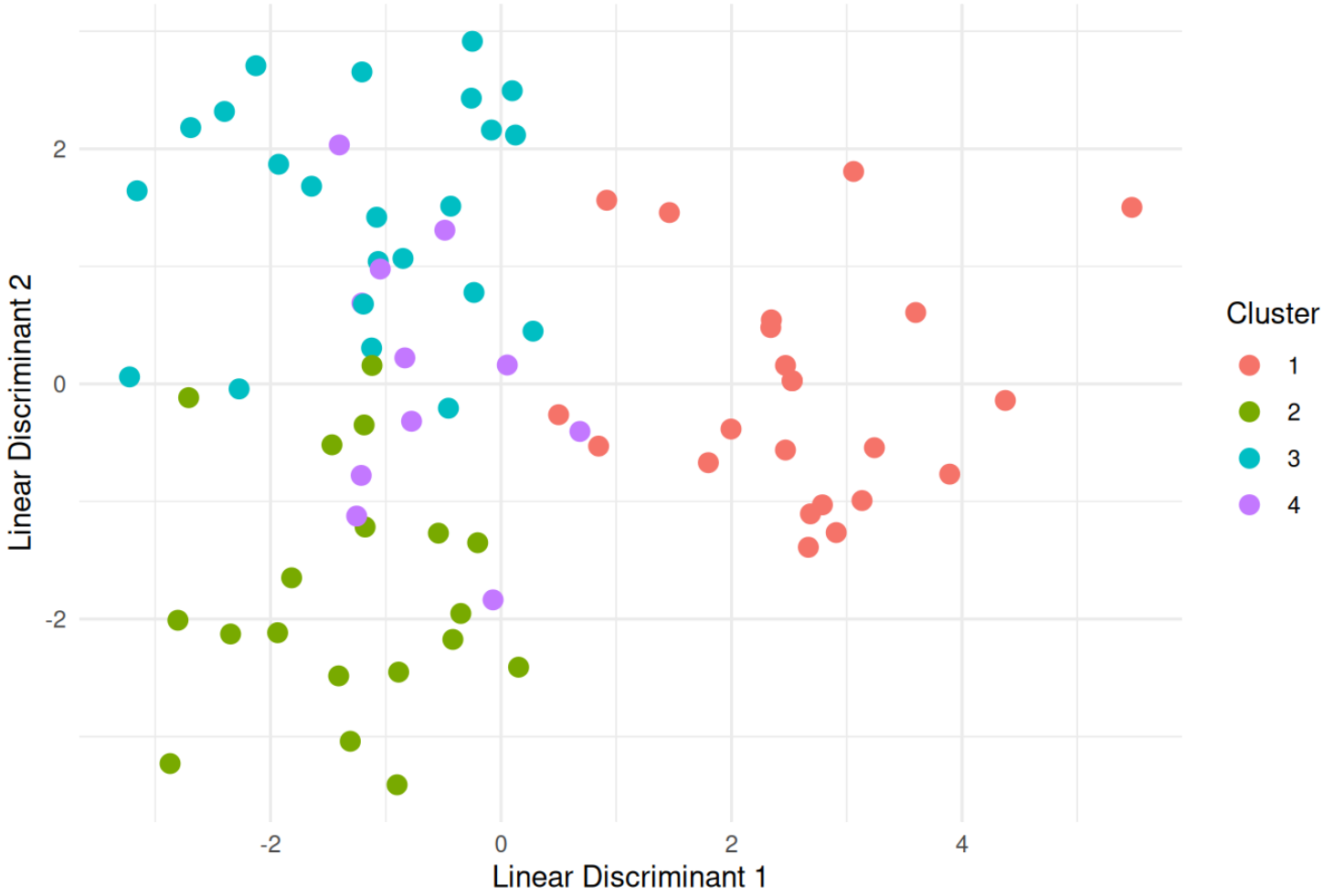


Figure 4

Linear discriminant analysis plot showing separation of farms into four biosecurity clusters

Multicollinearity among predictors was minimal (VIF range: 1.14–1.60; Table 5). Random forest classification independently confirmed transportation biosecurity, animal introduction practices, and visitor management as the most important determinants of cluster membership (Figure 5). Multinomial logistic regression achieved perfect in-sample classification (100% accuracy; Supplementary Tables S11–S12), although this likely reflects strong cluster separation rather than model overfitting. These findings provide convergent validation of the structural importance of these subcategories, consistent with PCA and LDA results.

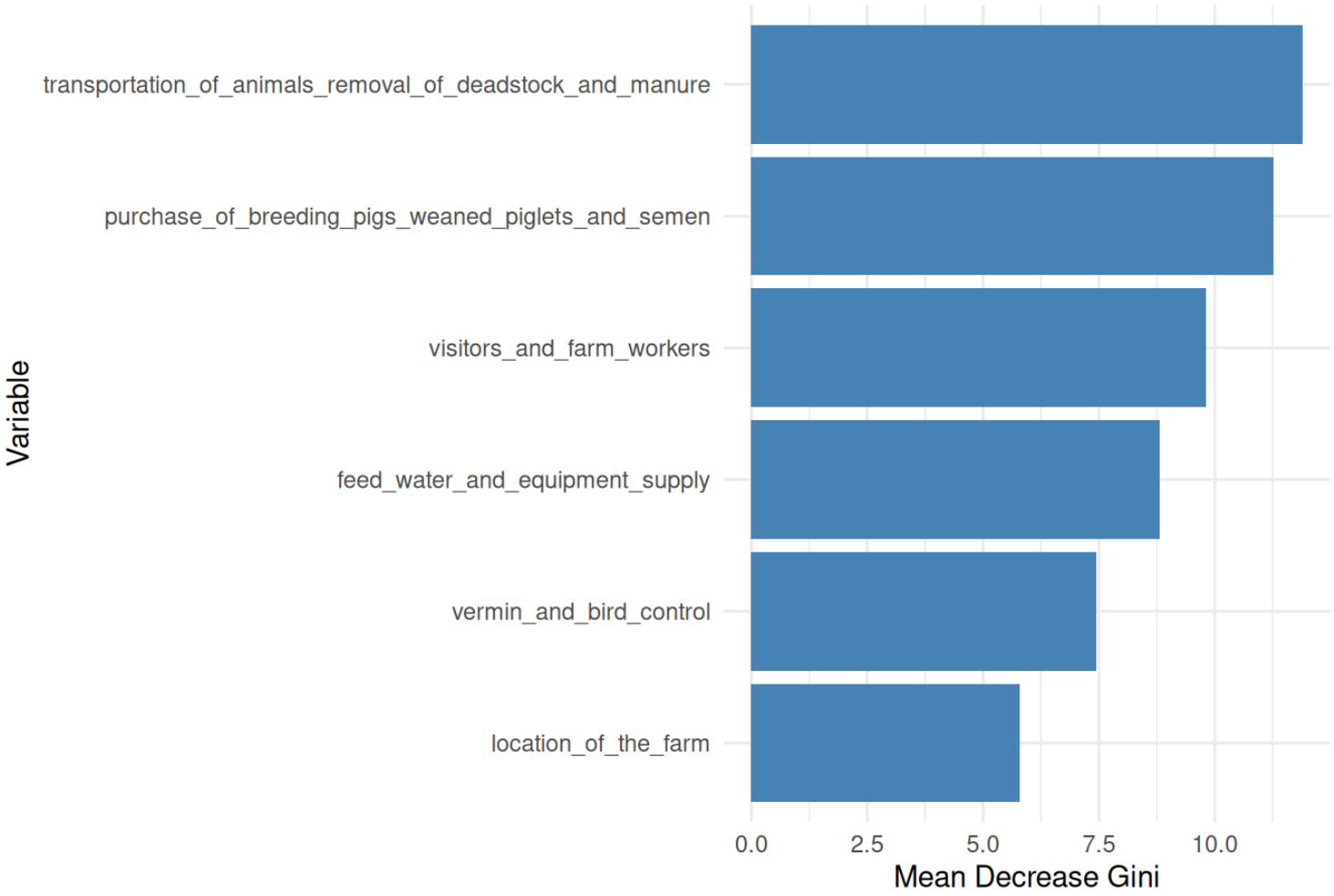


Figure 5

Random forest classification plot showing prediction accuracy and cluster separation.

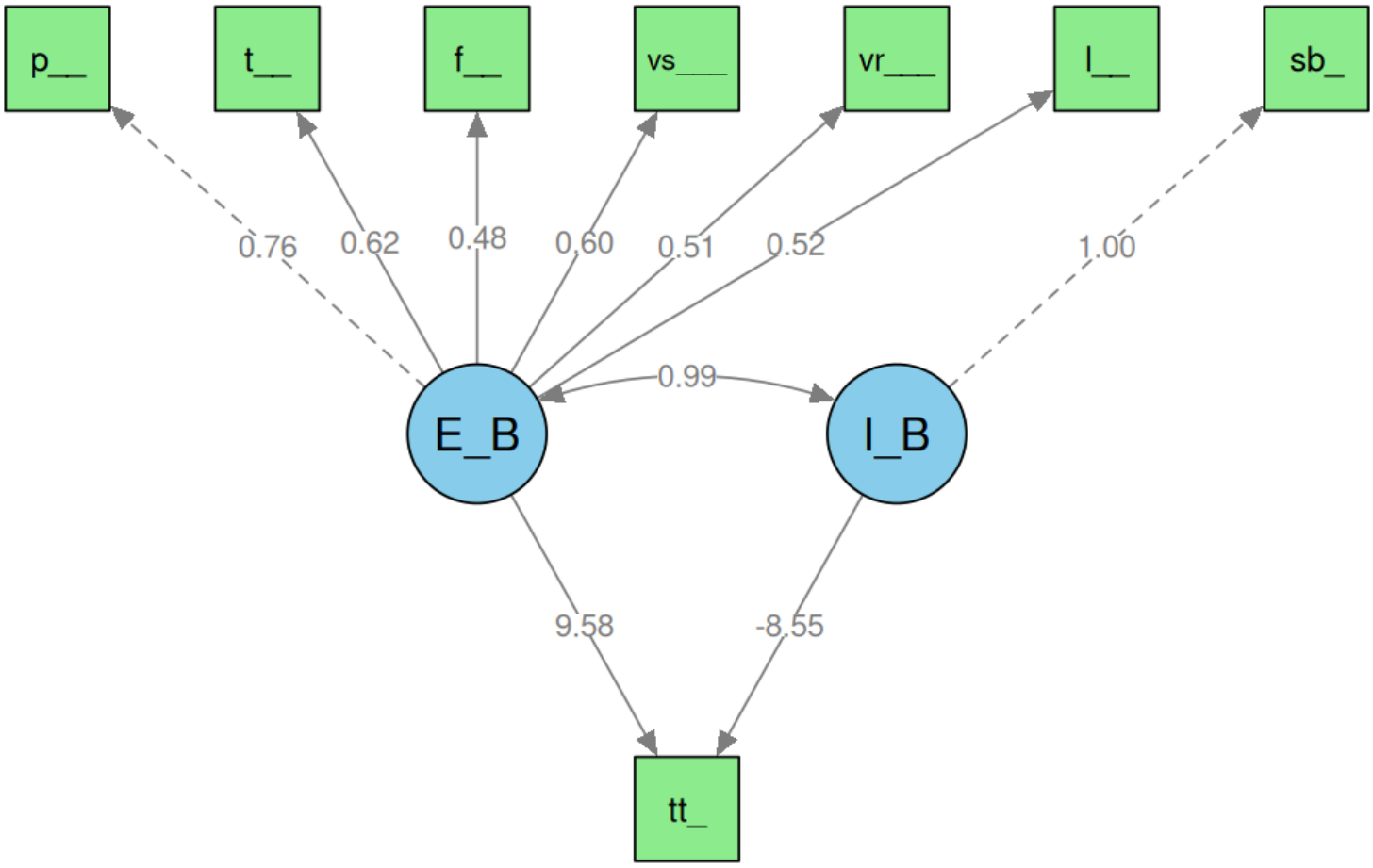


Figure 6

Structural equation model showing latent external biosecurity construct and its relationship with total biosecurity score among pig farms (n = 76).

Footnote: This path diagram represents the structural equation model examining latent external biosecurity as a second-order construct. Rectangles indicate observed variables (external biosecurity subcategories A-F). The circle represents the latent variable (External Biosecurity). Numbers adjacent to arrows from the latent variable to observed variables are standardized factor loadings, indicating the strength of relationship between each subcategory and the underlying construct (all p < 0.001). The arrow from latent external biosecurity to Total Biosecurity Score (rectangle) represents the structural regression path, with the standardized coefficient (1.20, p < 0.001) indicating that a one-standard-deviation increase in latent external biosecurity is associated with a 1.20-standard-deviation increase in overall biosecurity performance. This confirms external biosecurity as the dominant determinant of total biosecurity.

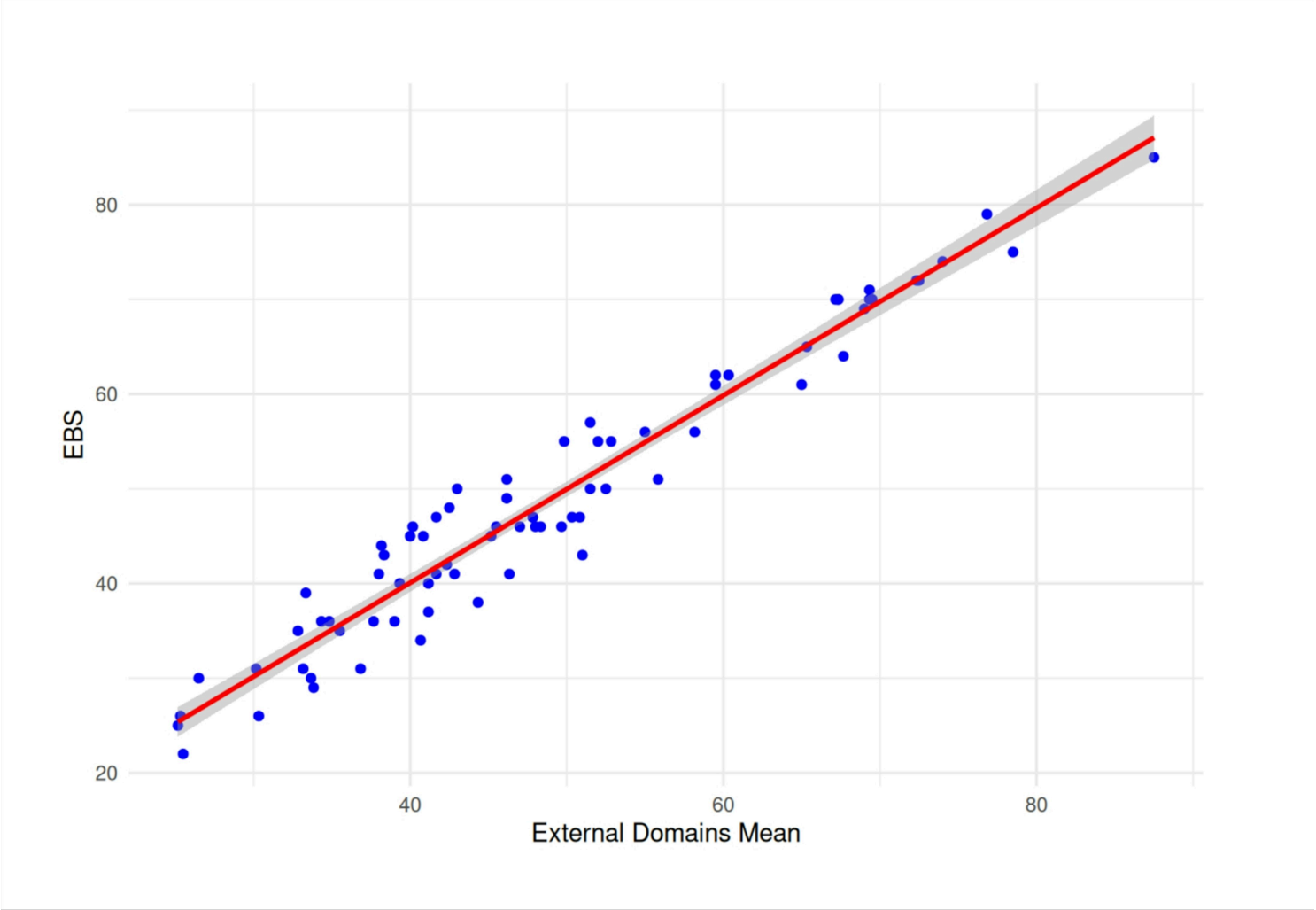


Figure 7

Correlation Between Composite External Biosecurity Subcategory Scores and External Biosecurity Index. Strong positive correlation confirming construct validity of composite biosecurity score (r = 0.971).

Note that domain also refer to subcategory.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementaryfiles.docx