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RESEARCH ARTICLE

Comparative Analysis of Biosecurity Practices, Antimicrobial Usage and Antimicrobial Resistance in Korean Pig Farms by Farm Type

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A B S T R A C T

Pig farming is a major sector of animal agriculture in Korea. Biosecurity practices and responsible antimicrobial use are key components in reducing disease incidence and mitigating antimicrobial resistance in swine production. This study aimed to compare biosecurity practices, antimicrobial usage, and antimicrobial resistance profiles across conventional, integrated, and grandparent (GP) pig farms in Korea. Data were collected from 69 pig farms (30 conventional, 30 integrated, and 9 GP) using detailed questionnaires and antimicrobial susceptibility testing of *Escherichia coli*. GP farms exhibited significantly higher productivity, with 77.8% achieving more than 23 marketed-pigs-per-sow-per-year and 44.4% having livability rates over 96%, outperforming conventional (20.0, 20.0%) and integrated farms (36.7, 26.7%). GP farms also demonstrated stricter biosecurity, including 100% adherence to farm-only vehicle use, regular veterinarian evaluation, and stringent access controls. Antimicrobial usage was lowest on GP farms (7.3±4.3 prescriptions) compared to conventional farms (9.7±7.4). Conventional farms exhibited the highest resistance to critical antimicrobials such as ceftiofur (conventional: 41.5; integrated: 23.9; GP: 21.8%) and ciprofloxacin (conventional: 51.0; integrated: 45.4; GP: 33.9%). The 14.4% of conventional isolates were resistant to 10 antimicrobial subclasses, compared to just 1.7 and 1.6% in integrated and GP farms, respectively. Stricter biosecurity and more prudent antimicrobial use in GP and integrated farms were associated with lower resistance rates, highlighting the importance of enhanced stewardship and management practices in conventional farms. These findings can also inform the development of policies and guidelines for sustainable and responsible pig production, aiming to reduce antimicrobial usage in Korea.

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INTRODUCTION

Antimicrobials have been widely used in livestock production to prevent and treat infectious diseases (Caneschi *et al.*, 2023). However, the emergence and spread of antimicrobial-resistant bacteria have led to increasing cases of treatment failure, posing serious threats to both animal and human health (EFSA, 2021). In response, global health organization such as the World Health Organization (WHO), the World Organization for Animal Health (WOAH; OIE), and the Food and Agriculture Organization have emphasized the urgent need to combat antimicrobial resistance (Seo *et al.*, 2023).

Biosecurity is crucial for preventing disease transmission in pig farming, involving measures to keep pathogens and wild animals off farms (Kidsley *et al.*, 2018; Yun *et al.*, 2021). Key practices include regulating transport, controlling visitor access, deterring wild birds, maintaining secure fencing, and implementing thorough disinfection and cleaning protocols for pig housing (Renault *et* al., 2021). These biosecurity measures are particularly important in addressing antimicrobial resistance, a growing concern in agriculture due to the overuse and misuse of antimicrobials (Abubakar *et al.*, 2019; Andersen *et al.*, 2023). Previous studies have reported that high-level biosecurity can prevent disease outbreaks, thereby reducing the need for antimicrobials in healthy pigs (Renault *et al.*, 2021; Harlow *et al.*, 2024).

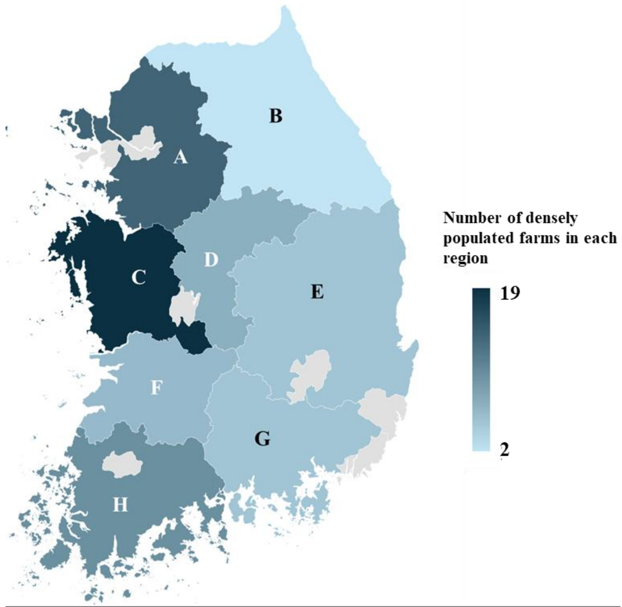
Pig farming systems in Korea primarily consist of grandparent (GP), integrated, and conventional farms (Seo *et al.*, 2023). GP farms, which specialize in producing genetically superior pigs for breeding, are particularly noted for their stringent biosecurity (Alarcón *et al.*, 2021; Renault *et al*., 2021; Wang *et al*., 2023). Also, integrated farms combine company-owned and contract farms with related enterprises (breeding, feed mills, transport, etc.), aiming to standardize production and implement high biosecurity (Szymańska, 2017; Seo *et al.*, 2023). Meanwhile, conventional farms often have fewer resources, rely heavily on manual labor (Maes *et al.*, 2020; Pexas *et al*., 2023), and may be less likely to invest in robust biosecurity measures (Seo *et al.*, 2023). Consequently, disease rates are higher, and treatments are often delayed, resulting in lower productivity (Maes *et al.*, 2020; Pexas *et al*., 2023).

In many advanced pig-farming countries, a significant proportion of farms are integrated. For example, in the United States, over 95% of pig production comes from large-scale, integrated farms, while in Denmark, the proportion of integrated pig production can be as high as 70-80% (Wang *et al.*, 2024). In contrast, South Korea began transitioning to integrated farms in 1990, but the proportion of integration was still approximately 20% (Seo *et al.*, 2023). This difference suggests a potential gap in biosecurity standards and antimicrobial usage across different farm types, thereby influencing the prevalence of antimicrobial resistance. This study aims to systematically examine the interrelationships among biosecurity practices, antimicrobial usage, and antimicrobial resistance in conventional, integrated, and GP pig farms in Korea.

MATERIALS AND METHODS

Study design: A total of 69 pig farms (30 conventional, 30 integrated, and 9 GP) were selected to represent the major pig production systems across Korea. Recruitment was conducted on a voluntary basis through veterinary networks and industry partnerships. Although randomization was not applied, stratified selection was used to ensure diversity in geographic location and operational characteristics (Fig. 1). The sample size was determined based on feasibility of farm access and anticipated variation in biosecurity practices. The smaller number of GP farms reflected their limited national distribution and restricted access, which presented logistical challenges for participation.

The questionnaires were developed with reference to national biosecurity and antimicrobial use guidelines and was reviewed by veterinary epidemiologists and field veterinarians to ensure content validity (Lee, 2023). Prior to implementation, the questionnaire was pilot-tested on five farms to assess clarity and feasibility, with subsequent revisions made accordingly. Data was collected through structured questionnaires covering farm environment, antimicrobial and disinfectant use, and biosecurity and management practices. Each questionnaire was completed jointly by the farm owner and the attending veterinarian.



Provinces	No. of farms			
	Conventional farms (n = 30) n(%)	Integrated farms (n = 30) n(%)	GP farms (n = 9) n(%)	Total (n = 69) n(%)
A	5(16.7)	8(26.7)	1(11.1)	14(20.3)
B	1(3.3)	0(0.0)	1(11.1)	2(2.9)
C	9(30.0)	9(30.0)	1(11.1)	19(27.5)
D	3(10.0)	3(10.0)	1(11.1)	7(10.1)
E	4(13.3)	0(0.0)	1(11.1)	5(7.2)
F	1(3.3)	4(13.3)	1(11.1)	6(8.7)
G	4(13.3)	0(0.0)	0(0.0)	4(5.8)
H	3(10.0)	6(20.0)	3(33.3)	12(17.4)

Fig. 1: Distribution of conventional, integrated, and grandparent (GP) farms in Korea. The farms were located across the country, with the intensity of color in each square reflecting the density of farms in that region.

Sample collection, processing and isolation of *Escherichia coli:* Between 2021 and 2022, five individual fecal samples of approximately 5g each were collected per farm shortly after defecation using sterile gauze swabs and transported to the laboratory on ice packs within one day. Upon arrival, each sample was streaked onto MacConkey agar plates (BD) and incubated aerobically at 37°C for 18–24h. To reflect within-farm microbiological diversity, three morphologically typical *Escherichia coli* colonies were selected per sample, targeting different pig production stages (suckling, weaned, grower, finisher, and sow) where applicable. This resulted in approximately 13–15 isolates per farm, and a total of 926 isolates across 69 farms (388 from conventional farms, 414 from integrated farms, and 124 from GP farms). Isolates were confirmed as *E. coli* using a polymerase chain reaction, as previously described (Seo *et al.*, 2023). Each isolate was treated as an independent observation for antimicrobial susceptibility testing. No statistical adjustment was made for farm-level clustering at the farm level, given the exploratory aim to capture both within- and between-farm variation.

Antimicrobial susceptibility test: All *E. coli* isolates underwent antimicrobial susceptibility testing using the disc diffusion method in accordance with Clinical and

Laboratory Standards Institute (CLSI) guidelines (CLSI, 2023). Test panels consisted of 23 antimicrobials spanning multiple classes recommended by the CLSI guidelines and commonly used in Korean swine production. All antimicrobial discs were sourced from Becton-Dickinson (USA). Isolates classified as intermediate were not considered resistant.

Statistical analysis: All statistical analyses were performed using SPSS version 27 (SPSS, Armonk, NY, USA). A one-way ANOVA was employed to compare the characteristics of conventional, integrated, and GP farms. Chi-square test was employed to compare the antimicrobial resistance rates of *E. coli* among the farm types. A *p*-value < 0.05 was considered statistically significant.

RESULTS

Farm productivity and Housing characteristics: Table 1 provides the production performance of 69 pig farms in Korea. GP farms more frequently exceeded the performance thresholds for Marketed-pigs per Sow per Year (MSY; 77.8% for 'over 23'), and livability (44.4% for 'over 96%' than integrated (36.7, 26.7%), and conventional (20.0, 20.0%) farms. As shown in Table 2, GP farms exclusively used windowless housing and mechanical ventilation, while conventional farms showed the lowest adoption of these systems.

Table 1: Production performance of conventional, integrated, and GP farms in Korea

Subgroup	No. of farms			
	Conventional farms (n=30); n(%)	Integrated farms (n=30) n(%)	GP farms (n=9) n(%)	Total (n=69) n(%)
Marketed-pigs per Sow per Year				
under 20	8(26.7)^{a}	6(20.0)^{a}	0(0.0)^{b}	14(20.3)^{AB}
20 to 22	10(33.3)	7(23.3)	2(22.2)	19(27.5)^{AB}
22 to 23	6(20.0)^{a}	6(20.0)^{a}	0(0.0)^{b}	12(17.4)^{B}
over 23	6(20.0)^{b}	11(36.7)^{c}	7(77.8)^{a}	24(34.8)^{A}
Livability (%)[1)]				
under 88	10(33.3)^{a}	7(23.3)^{a}	0(0.0)^{b}	17(24.6)
88 to 93	6(20.0)	7(23.3)	1(11.1)	14(20.3)
93 to 96	8(26.7)^{b}	8(26.7)^{b}	4(44.4)^{a}	20(29.0)
over 96	6(20.0)^{b}	8(26.7)^{b}	4(44.4)^{a}	18(26.1)

[1)] Livability (%): The percentage of pigs that survive from birth to market stage. Different lowercase subscript letters indicate significant differences among farm types, while values with different uppercase subscript letters denote significant differences between total response subgroups (P<0.05).

Vehicle Biosecurity Management: Table 3 shows that all GP farms used farm-only vehicles for slaughter/transport, whereas this was observed in only 30.0 and 23.3% of integrated and conventional farms, respectively. Vehicle disinfection was nearly universal (97.1%, overall), but only GP and integrated farms disinfected all incoming vehicles without exception. Driver access restrictions were strictest in GP farms (0% allowed), compared to integrated (16.7%) and conventional farms (13.3%). Feed transport vehicles were not allowed in GP farms (100%), unlike integrated (36.7%) and conventional farms (43.3%).

Control of Environmental Pathogen Exposure: Table 4 shows that 95.7% of farms had fences. GP farms had 100% fencing, integrated 93.3%, and conventional farms 96.7%. None of the GP farms allowed bird access, whereas 60.0% of conventional farms did. Veterinary evaluations were regular in 100% of GP, 86.7% of integrated, and 46.7% of conventional farms.

Table 2: Housing and ventilation systems of conventional, integrated, and GP farms in Korea

Subgroup	No. of farms			
	Conventional farms n(%)	Integrated farms n(%)	GP farms n(%)	Total n(%)
Housing system				
Suckling piglets	(n=30)	(n=30)	(n=9)	(n= 69)
Windowless house	14(46.7)^{c}	25(83.3)^{b}	9(100.0)^{a}	48(69.6)$_{A}$
Windowed house	3(10.0)^{a}	3(10.0)^{a}	0(0.0)^{b}	6(8.7)$_{B}$
Combination	13(43.3)^{a}	2(6.7)^{b}	0(0.0)^{c}	15(21.7)$_{B}$
Weaned piglets	(n=30)	(n=30)	(n=9)	(n= 69)
Windowless house	23(76.7)^{b}	26(86.7)^{b}	9(100.0)^{a}	58(84.1)$_{A}$
Windowed house	1(3.3)^{ab}	3(10.0)^{a}	0(0.0)^{b}	4(5.8)$_{B}$
Combination	6(20.0)^{a}	1(3.3)^{b}	0(0.0)^{b}	7(10.1)$_{B}$
Grower pigs	(n=30)	(n=30)	(n=9)	(n= 69)
Windowless house	15(50.0)^{c}	26(86.7)^{b}	9(100.0)^{a}	50(72.5)$_{A}$
Windowed house	4(13.3)^{a}	3(10.0)^{a}	0(0.0)^{b}	7(10.1)$_{B}$
Combination	11(36.7)^{a}	1(3.3)^{b}	0(0.0)^{b}	12(17.4)$_{B}$
Finisher pigs	(n=30)	(n=30)	(n=9)	(n= 69)
Windowless house	12(40.0)^{c}	17(56.7)^{b}	9(100.0)^{a}	38(55.1)$_{A}$
Windowed house	4(13.3)^{a}	7(23.3)^{a}	0(0.0)^{b}	11(15.9)$_{B}$
Combination	14(46.7)^{a}	6(20.0)^{b}	0(0.0)^{c}	20(29.0)$_{B}$
Sow	(n=30)	(n=30)	(n=9)	(n= 69)
Windowless house	9(30.0)^{c}	21(70.0)^{b}	9(100.0)^{a}	39(56.5)$_{A}$
Windowed house	7(23.3)^{a}	7(23.3)^{a}	0(0.0)^{b}	14(20.3)$_{B}$
Combination	14(46.7)^{a}	2(6.7)^{b}	0(0.0)^{c}	16(23.2)$_{B}$
Total	(n=150)	(n=150)	(n=45)	(n=345)
Windowless house	73(48.7)^{c}	115(76.7)^{b}	45(100.0)^{a}	233(67.5)$_{A}$
Windowed house	19(12.7)^{a}	23(15.3)^{a}	0(0.0)^{b}	42(12.2)$_{B}$
Combination	58(38.7)^{a}	12(8.0)^{b}	0(0.0)^{c}	70(20.3)$_{B}$
Ventilation system				
Suckling piglets	(n=30)	(n=30)	(n=9)	(n= 69)
Mechanical	15(50.0)^{c}	26(86.7)^{b}	9(100.0)^{a}	50(72.5)$_{A}$
Natural	0(0.0)	0(0.0)	0(0.0)	0(0.0)$_{B}$
Combination	15(50.0)^{a}	4(13.3)^{b}	0(0.0)^{c}	19(27.5)$_{C}$
Weaned piglets	(n=30)	(n=30)	(n=9)	(n= 69)
Mechanical	24(80.0)^{b}	25(83.3)^{b}	9(100.0)^{a}	58(84.1)$_{A}$
Natural	0(0.0)	1(3.3)	0(0.0)	1(1.4)$_{B}$
Combination	6(20.0)^{a}	4(13.3)^{a}	0(0.0)^{b}	10(14.5)$_{C}$
Grower pigs	(n=30)	(n=30)	(n=9)	(n= 69)
Mechanical	17(56.7)^{b}	26(86.7)^{c}	9(100.0)^{a}	52(75.4)$_{A}$
Natural	0(0.0)	1(3.3)	0(0.0)	1(1.4)$_{B}$
Combination	13(43.3)^{a}	3(10.0)^{b}	0(0.0)^{c}	16(23.2)$_{C}$
Finisher pigs	(n=30)	(n=30)	(n=9)	(n= 69)
Mechanical	15(50.0)^{b}	17(56.7)^{b}	9(100.0)^{a}	41(59.4)$_{A}$
Natural	0(0.0)	2(6.7)	0(0.0)	2(2.9)$_{B}$
Combination	15(50.0)^{a}	11(36.7)^{a}	0(0.0)^{b}	26(37.7)$_{C}$
Sow	(n=30)	(n=30)	(n=9)	(n= 69)
Mechanical	9(30.0)^{b}	21(70.0)^{c}	9(100.0)^{a}	39(56.5)$_{A}$
Natural	3(10.0)^{a}	3(10.0)^{a}	0(0.0)^{b}	6(8.7)$_{C}$
Combination	18(60.0)^{a}	6(20.0)^{b}	0(0.0)^{c}	24(34.8)$_{B}$
Total	(n=150)	(n=150)	(n=45)	(n=345)
Mechanical	80(53.3)^{c}	115(76.7)^{b}	45(100.0)^{a}	240(69.6)$_{A}$
Natural	3(2.0)^{ab}	7(4.7)^{a}	0(0.0)^{b}	10(2.9)$_{C}$
Combination	67(44.7)^{a}	28(18.7)^{b}	0(0.0)^{c}	95(27.5)$_{B}$

Different lowercase subscript letters indicate significant differences among farm types, while uppercase subscript letters denote significant differences between total response subgroups (P<0.05).

Personnel access and Hygiene control: Table 5 indicates that 87.0% of pig farms had farm access regulations. GP farms showed 100% compliance with access rules and separation of clean/dirty areas, while lower rates were observed in integrated (63.3%) and conventional farms (56.7%). Quarantine manuals were most commonly used in GP farms (88.9%), followed by conventional (56.7%), and integrated farms (46.7%).

Table 3: Analysis of vehicle management of conventional, integrated, and GP farms in Korea

Questionnaire Responses	No. of farms			
	Conventional farms (n=30) n(%)	Integrated farms (n=30) n(%)	GP farms (n=9) n(%)	Total (n=69) n(%)
What is the vehicle control for slaughtering or transporting pigs?				
No vehicle control is implemented.	1(3.3)	0(0.0)	0(0.0)	1(1.4)$_{C}$
The same vehicle accesses multiple farms, but vehicles are washed and disinfected before arrival.	22(73.3)^{a}	21(70.0)^{a}	0(0.0)^{b}	43(62.3)$_{A}$
A farm-specific vehicle is used.	7(23.3)^{b}	9(30.0)^{b}	9(100.0)^{a}	25(36.2)$_{B}$
Is the transport vehicle for piglets cleaned and disinfected upon arrival at the farm?				
No information available regarding cleaning and disinfection.	2(6.7)^{a}	0(0.0)^{b}	0(0.0)^{b}	2(2.9)$_{B}$
Always cleaned and disinfected.	28(93.3)^{b}	30(100.0)^{a}	9(100.0)^{a}	67(97.1)$_{A}$
Does the driver have access to the stables during animal loading?				
The driver exits the vehicle and may approach the stables.	4(13.3)^{a}	5(16.7)^{a}	0(0.0)^{b}	9(13.0)$_{B}$
The driver remains in the vehicle and does not approach the stables.	13(43.3)^{a}	14(46.7)^{a}	0(0.0)^{b}	27(39.1)$_{A}$
Loading platforms are located outside the farm premises.	13(43.3)^{b}	11(36.7)^{b}	9(100.0)^{a}	33(47.8)$_{A}$
Are hygiene standards (e.g. cleaning and disinfection of the vehicle) for transport vehicles delivering feed to the farm followed?				
No hygienic standards are applied to transport vehicles.	3(10.0)^{a}	0(0.0)^{b}	0(0.0)^{b}	3(3.3)$_{C}$
Transport vehicles may visit multiple farms, but they must be cleaned and disinfected each time.	22(73.3)^{b}	26(86.7)^{a}	0(0.0)^{c}	48(69.6)$_{A}$
Transport vehicles do not enter the farm; instead, feed is delivered from the outside.	5(16.7)^{b}	4(13.3)^{b}	9(100.0)^{a}	18(18.1)$_{B}$

Different lowercase subscript letters indicate significant differences among farm types, while uppercase subscript letters denote significant differences between total response subgroups (P<0.05).

Table 4: Analysis of outdoor access management across conventional, integrated, and GP farms in Korea

Questionnaire Responses	No. of farms			
	Conventional farms (n=30) n(%)	Integrated farms (n=30) n(%)	GP farms (n=9) n(%)	Total (n=69) n(%)
Is there a fence around the farm?				
Yes	29(96.7)^{ab}	28(93.3)^{b}	9(100.0)^{a}	66(95.7)$_{A}$
No	1(3.3)^{ab}	2(6.7)^{a}	0(0.0)^{b}	3(4.3)$_{B}$
Do birds have access to the stables?				
Yes	18(60.0)^{a}	6(20.0)^{b}	0(0.0)^{c}	24(34.8)$_{B}$
No	12(40.0)^{c}	24(80.0)^{b}	9(100.0)^{a}	45(65.2)$_{A}$
Is the farm's disease status regularly evaluated by a veterinarian?				
Regular evaluations	14(46.7)^{c}	26(86.7)^{b}	9(100.0)^{a}	49(71.0)$_{A}$
Irregular evaluations	16(53.3)^{a}	4(13.3)^{b}	0(0.0)^{c}	20(29.0)$_{B}$
Is the composting area protected from wild birds or rodents?				
Yes	21(70.0)^{a}	18(60.0)^{a}	4(44.4)^{b}	43(62.3)$_{A}$
No	9(30.0)^{b}	12(40.0)^{b}	5(55.6)^{a}	26(37.7)$_{B}$
Do you regularly perform and record internal and outdoor disinfection?				
Yes	27(90.0)^{b}	26(86.7)^{b}	9(100.0)^{a}	62(89.9)$_{A}$
No	3(10.0)^{a}	4(13.3)^{a}	0(0.0)^{b}	7(10.1)$_{B}$
How do you manage biosecurity between pig houses?[1)]				
No biosecurity measures	3(10.0)^{a}	1(3.3)^{b}	0(0.0)^{b}	4(5.8)$_{B}$
Shoe washing at the doorway	21(70.0)^{a}	16(53.3)^{b}	4(44.4)^{b}	41(59.4)$_{A}$
Wearing farm-specific clothing and shoes at the doorway	17(56.7)	15(50.0)	4(44.4)	36(52.2)$_{A}$
Other measures	4(13.3)^{b}	0(0.0)^{c}	4(44.4)^{a}	8(11.6)$_{B}$

[1)] Multiple responses were allowed in this section of the questionnaire. Different lowercase subscript letters indicate significant differences among farm types, while uppercase subscript letters denote significant differences between total response subgroups (P<0.05).

Table 5: Analysis of personnel management practices across conventional, integrated, and GP farms in Korea

Questionnaire Responses	No. of farms			
	Conventional farms (n=30) n(%)	Integrated farms (n=30) n(%)	GP farms (n=9) n(%)	Total (n=69) n(%)
Are there any farm access requirements for visitors, including veterinarians?				
Yes	21(70.0)^{b}	30(100.0)^{a}	9(100.0)^{a}	60(87.0)$_{A}$
No visitors are allowed to enter the stables.	3(10.0)^{a}	0(0.0)^{b}	0(0.0)^{b}	3(4.3)$_{B}$
No	6(20.0)^{a}	0(0.0)^{b}	0(0.0)^{b}	6(8.7)$_{B}$
Is there any separation area between the clean and the dirty areas?				
No separation between clean and dirty areas.	3(10.0)^{a}	0(0.0)^{b}	0(0.0)^{b}	3(4.3)$_{C}$
Separation exists not always strictly applied.	10(33.3)^{a}	11(36.7)^{a}	0(0.0)^{b}	21(30.4)$_{B}$
Strict separation between clean and dirty areas, with all visitors required to sign a guest book upon entry.	17(56.7)^{b}	19(63.3)^{b}	9(100.0)^{a}	45(65.2)$_{A}$
Is there a farm quarantine manual?				
No quarantine manual and no worker education.	3(10.0)^{a}	4(13.3)^{a}	0(0.0)^{b}	7(10.1)$_{C}$
Quarantine manual sometimes used for training, but not kept on the farm.	10(33.3)^{a}	12(40.0)^{a}	1(11.1)^{b}	23(33.3)$_{B}$
Quarantine manual used for training and kept on the farm for workers to access.	17(56.7)^{b}	14(46.7)^{b}	8(88.9)^{a}	39(56.5)$_{A}$

Different lowercase subscript letters indicate significant differences among farm types, while uppercase subscript letters denote significant differences between total response subgroups (P<0.05).

Patterns of antimicrobial usage: Table 6 presents a comparative analysis of antimicrobial use. β-lactams were the most frequently used (3.5±2.9), followed by aminoglycosides and fluoroquinolones. Phenicols were more commonly prescribed in conventional farms (1.4±1.4) than in GP farms (0.1±0.3). Weaned piglets received the highest number of prescriptions, particularly in conventional farms (3.2±2.1) compared to GP farms (1.7±0.5). No preventive prescriptions were recorded in GP farms.

Table 6: Antimicrobial use in conventional, integrated, and GP farms in Korea

Subgroup	Conventional farms	Integrated farms	GP farms	Total
No. of Prescriptions	9.7±7.4	7.3±6.0	7.3±4.3	8.3±6.5
Antimicrobial class [1)]				
Aminoglycosides	3.1±2.5	1.8±3.1	1.2±1.9	2.3±2.8$_B$
β-lactams	3.7±2.4	3.1±3.4	3.9±2.8	3.5±2.9$_A$
Fluoroquinolones	1.6±1.6	1.3±1.2	1.2±1.6	1.4±1.4$_C$
Lincosamides	0.4±0.4	0.8±0.3	0.0±0.0	0.5±1.1$_{DEF}$
Macrolides	1.3±1.3	0.7±1.9	1.0±1.1	1.0±1.7$_{CD}$
Phenicols	1.4±1.4^a	0.5±1.8^{ab}	0.1±0.3^b	0.8±1.5$_{CDE}$
Pleuromutilins	0.3±0.3	0.2±0.4	0.2±0.4	0.2±0.8$_F$
Polypeptides	0.2±0.2	0.4±0.0	0.1±0.3	0.3±0.7$_{EF}$
Sulfonamides	0.3±0.3	0.1±0.4	0.0±0.0	0.2±0.5$_F$
Tetracyclines	0.3±0.3	0.1±0.3	0.1±0.3	0.2±0.8$_F$
Antimicrobial use by production stage				
Suckling piglet	1.8±2.5	1.5±1.0	2.1±1.7	1.7±1.9$_B$
Weaned piglet	3.2±2.1^a	2.2±3.6^{ab}	1.7±0.5^b	2.6±1.8$_A$
Grower pig	2.2±2.1^a	0.9±2.2^b	1.8±1.6^{ab}	1.6±1.8$_C$
Finisher pig	1.2±1.8	0.9±1.5	0.7±1.1	1.0±1.6$_C$
Sow	1.2±1.8	1.8±1.2	1.1±1.2	1.5±1.9$_{BC}$
Reason				
Treatment	5.5±5.3^{ab}	3.1±2.5^b	7.3±4.3^a	4.7±4.4$_A$
Prevention	4.1±2.9^a	4.2±4.2^a	0.0±0.0^b	3.6±3.6$_A$
Growth	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0$_B$
Performance of susceptibility test				
Yes	0.3±1.5^b	0.5±1.3^b	4.0±4.8^a	0.9±2.4$_B$
No	9.4±7.6^a	6.8±6.3^{ab}	3.3±5.0^b	7.5±7.0$_A$

Data were presented as the average number of prescriptions±standard deviation. Different lowercase subscript letters indicate significant differences among farm types, while uppercase subscript letters denote significant differences between total response subgroups (P<0.05).[1)] More than one antimicrobial subclass could be included in a single prescription.

Antimicrobial resistance phenotypes and multidrug resistance profiles of *E. coli:* Table 7 summarizes antimicrobial resistance profiles of *E. coli* across farm types. Conventional farms showed significantly higher resistance to several antimicrobials including: amplicillin (88.7%), ceftiofur (41.5%), and florfenicol (76.8%), compared to integrated (77.3, 23.9, 62.8%) and GP farms (68.5, 21.8, 51.6%), respectively. A similar trend was observed for phenicols, with conventional farms showing the highest resistance rates.

Table 8 compares multidrug resistance patterns by farm type. Over 90% of isolates across all farm types were multi-drug resistant (conventional farms: 95.6%, integrated farms: 91.3%, GP farms: 90.3%). However, the proportion of isolates resistant to 10 antimicrobial subclasses was significantly higher on conventional farms (14.4%) compared to integrated farms (1.7%) and GP farms (1.6%).

DISCUSSION

In this study, GP farms showed the highest productivity, which may be attributable to their consistent use of windowless housing and mechanical ventilation. These systems support environmental stability, potentially reducing disease risk and improving growth performance (Alarcón *et al*., 2021; Renault *et al*., 2021; Harlow *et al.*, 2024). In contrast, conventional farms relied more on mixed housing and ventilation systems, particularly for weaned piglets, which are more vulnerable to respiratory infections (Do *et al*., 2020a). The observed differences suggest that adopting more standardized housing and ventilation strategies could enhance productivity in conventional settings.

Table 7: Antimicrobial resistance phenotypes of *E. coli* from conventional, integrated, and GP farms in Korea

Antimicrobial agents	Conventional farms (n=388) n(%)	Integrated farms (n=414) n(%)	GP farms (n=124) n(%)
β-lactams			
Ampicillin	344(88.7)^a	320(77.3)^b	85(68.5)^b
Amoxicillin-clavulanate	61(15.7)	35(8.5)	16(12.9)
Piperacillin-tazobactam	92(23.7)^a	4(1.0)^b	1(0.8)^b
Meropenem	0(0.0)	0(0.0)	0(0.0)
Cephems			
Cefazolin	343(88.4)^a	296(71.5)^b	92(74.2)^b
Cefuroxime	53(13.7)	32(7.7)	9(7.3)
Cefoxitin	38(9.8)	26(6.3)	11(8.9)
Ceftiofur	161(41.5)^a	99(23.9)^b	27(21.8)^b
Cefotaxime	48(12.4)	20(4.8)	8(6.5)
Ceftazidime	39(10.1)	15(3.6)	9(7.3)
Cefepime	29(7.5)	15(3.6)	6(4.8)
Aminogylcosides			
Gentamicin	130(33.5)^a	95(22.9)^a	14(11.3)^b
Streptomycin	332(85.6)^a	326(78.7)^{ab}	88(71.0)^b
Kanamycin	209(53.9)^a	211(51.0)^a	39(31.5)^b
Tetracyclines			
Oxytetracycline	212(54.6)^b	288(69.6)^a	83(66.9)^a
Tetracycline	203(52.3)^b	279(67.4)^a	76(61.3)^{ab}
Tigecycline	84(21.6)^a	1(0.2)^b	0(0.0)^b
Phenicols			
Florfenicol	298(76.8)^a	260(62.8)^b	64(51.6)^b
Chloramphenicol	311(80.2)^a	302(72.9)^{ab}	78(62.9)^b
Quinolone			
Nalidixic acid	198(51.0)	197(47.6)	55(44.4)
Ciprofloxacin	198(51.0)^a	188(45.4)^{ab}	42(33.9)^b
Sulfonamides			
Sulfisoxazole	316(81.4)	292(70.5)	86(69.4)
SXT[1)]	253(65.2)	256(61.8)	79(63.7)

Different lowercase subscript letters indicate significant differences among farm types, while uppercase subscript letters denote significant differences between total response subgroups (P<0.05). [1)] SXT: Trimethoprim-Sulfamethoxazole.

Table 8: Multi-drug resistance in *E. coli* from conventional, integrated, and GP farms in Korea

Multi-Drug Resistance Patterns	Conventional farms (n=388) n(%)	Integrated farms (n=414) n(%)	GP farms (n=124) n(%)
Non Multi-Drug Resistance	17(4.4)	36(8.7)	12(9.7)
0 subclass	2(0.5)	5(1.2)	4(3.2)
1 subclass	6(1.5)	13(3.1)	3(2.4)
2 subclasses	9(2.3)	18(4.3)	5(4.0)
Multi-Drug Resistance	371(95.6)	378(91.3)	112(90.3)
3 subclasses	11(2.8)^a	20(4.8)^{ab}	12(9.7)^b
4 subclasses	16(4.1)	47(11.4)	11(8.9)
5 subclasses	36(9.3)	31(7.5)	16(12.9)
6 subclasses	56(14.4)	70(16.9)	20(16.1)
7 subclasses	60(15.5)	70(16.9)	18(14.5)
8 subclasses	59(15.2)	54(13.0)	17(13.7)
9 subclasses	77(19.8)	79(19.1)	16(12.9)
10 subclasses	56(14.4)^a	7(1.7)^b	2(1.6)^b

Different lowercase subscript letters indicate significant differences among farm types, while uppercase subscript letters denote significant differences between total response subgroups (P<0.05).

In this study, all vehicles used for pig transport in GP and integrated farms were cleaned and disinfected upon arrival, whereas 6.7% of vehicles in conventional farms lacked any record of cleaning and disinfection practices, showing a significant difference. Although using farm-only vehicles is ideal for preventing pathogen transmission between farms, transport vehicles should be thoroughly disinfected before arrival if this approach is not feasible (Alarcón *et al*., 2021). By implementing similar vehicle management protocols, conventional farms can reduce the risk of disease transmission, leading to healthier livestock and potentially higher productivity (Alarcón *et al*., 2021).

GP and integrated farms were more effective in preventing bird access to stables (0.0, 20.0%) and conducting regular veterinary evaluations (100.0, 86.7%) compared to conventional farms (60.0, 46.7%). These practices are crucial for maintaining high health standards and ensuring early disease detection (Caekebeke *et al.*, 2020; Alarcón *et al*., 2021; Renault *et al*., 2021; Makovska *et al.*, 2023). Wild birds can introduce pathogens into farms; therefore, installing farm fences is essential to minimize their contact with livestock (Alarcón *et al*., 2021; Makovska *et al.*, 2023; Wang *et al.*, 2023). In particular, wild birds can significantly contribute to pathogen transmission by acting as mechanical or biological vectors (Makovska *et al.*, 2023).

An analysis of personnel management practices on pig farms in Korea revealed that GP and integrated farms exhibited stricter control measures than conventional farms (70%). Such strict access control likely enhances biosecurity by limiting potential contamination sources (Caekebeke *et al.*, 2020; Alarcón *et al.*, 2021; Renault *et al*., 2021; Harlow *et al.*, 2024). Regarding the separation between clean and dirty areas, GP and integrated farms demonstrated better practices, whereas 10% of conventional farms had no separation. The strict separation maintained by integrated farms is important for upholding hygiene and preventing cross-contamination (Caekebeke *et al.*, 2020; Alarcón *et al.*, 2021; Renault *et al*., 2021; Harlow *et al.*, 2024). An assessment of overall biosecurity measures indicates that GP farms maintain the highest standards, particularly in preventing the introduction of external pathogens, disease prevention, and regular veterinary consultations. Although this study did not specifically measure disease incidence, the assumption that GP farms may experience fewer outbreaks is based on their consistently stricter biosecurity measures. However, this remains a limitation of the study and should be addressed in future research. This superior performance in GP farms is likely attributed to these effective biosecurity measures (Renault *et al.*, 2021; Harlow *et al.*, 2024) .

In this study, antimicrobials were not used for growth promotion on any of the farms, as Korea banned the use of antimicrobials in pig feed for growth promotion in 2011 (Do *et al*., 2020b). Nonetheless, conventional farms still showed significantly higher prescription rates (9.7±7.4) than integrated (7.3±6.0) or GP farms (7.3±4.3). Effective disease treatment requires the appropriate prescription of antimicrobials based on antimicrobial sensitivity tests. The markedly higher frequency of susceptibility testing in GP farms, compared to conventional and integrated farms, reflects a stronger commitment to evidence-based antimicrobial use (Andersen *et al.*, 2023; Caneschi *et al.*, 2023). Conducting susceptibility tests before prescribing helps minimize antimicrobial usage and mitigates public health risks.

In South Korea, antimicrobials are easily accessible to farmers (Do *et al*., 2020b; Jung *et al*., 2023), underscoring the need for stricter legal regulations on their use. Frequent antimicrobial prescriptions for weaned piglets highlight the need for careful health management during this critical period (Do *et al*., 2020b; Yun *et al.*, 2021). Similarly, we observed that antimicrobials were generally not used for grower pigs due to withdrawal periods, helping ensure meat safety (Yun *et al*., 2021). GP and integrated farms, with advanced infrastructure and strict biosecurity measures, demonstrated superior productivity. These results highlight the potential benefits for conventional farms to adopt similar practices.

The antimicrobial resistance profiles of *E. coli* showed that conventional farms generally exhibited higher resistance to most agents. In addition, resistance to critically important antimicrobials, which the WHO defines as including third-generation cephalosporins (ceftiofur, cefotaxime) and ciprofloxacin, was higher in conventional farms. Resistance to these critically important antimicrobials poses significant public health risks, as it limits treatment options for human infections (Do *et al.*, 2020a). It is well-established that more frequent antimicrobial use increases the likelihood of developing resistance (Do *et al*., 2020a). The higher resistance to phenicol antimicrobials in conventional farms likely reflects their more frequent usage, as indicated in Table 6, where conventional farms reported significantly higher prescription rates for phenicol agents.

In this study, conventional farms had a significantly higher percentage of *E. coli* resistant to 10 antimicrobial subclasses (14.4%) than GP farms (1.6%) and integrated farms (1.7%). This indicates that conventional farms face more severe multi-drug resistant bacteria issues, highlighting the urgent need for improved antimicrobial stewardship and stronger biosecurity (Yun *et al.*, 2021; Ager *et al.*, 2023). Consequently, it can be inferred that conventional farms may have less rigorous antimicrobial use practices and biosecurity, resulting in higher resistance rates and more severe multi-drug resistance challenges.

Consequently, it can be inferred that conventional farms may have less rigorous antimicrobial use practices and biosecurity, resulting in higher resistance rates and more severe multi-drug resistance. These findings underscore the need for targeted policy interventions. Conventional farms could benefit from enhanced support in adopting standardized antimicrobial use protocols including mandatory susceptibility testing and record-keeping. Additionally, incentive-based approaches such as government subsidies, or certification schemes may encourage compliance and facilitate the transition toward prudent antimicrobial stewardship.

Compared to international studies, the antimicrobial resistance observed in this study were notably higher than those reported in European countries. For example, ampicillin resistance in this study exceeded the typical 30-60% range reported in European pig farms (EFSA, 2021). These differences may reflect variations in national antimicrobial usage regulations, enforcement practices, and biosecurity standards. While many European countries restrict prophylactic and metaphylactic use of antimicrobials in livestock, antimicrobials remain more readily accessible in Korea (Jung *et al*., 2023). These findings highlight the urgent need for strengthening antimicrobial stewardship and implementing stricter biosecurity protocols in Korean pig production.

Conclusions: High-level biosecurity measures are crucial for preventing disease outbreaks, thereby reducing the need for antimicrobial use in healthy pigs (Renault *et al*., 2021; Harlow *et al.*, 2024). Conventional farms are often reluctant to implement such systems due to the high costs, which are usually privately funded (Niemi *et al.*, 2016; Seo *et al.*, 2023; Garg *et al.*, 2024). These findings can also inform the development of policies and guidelines for sustainable and responsible pig production, aiming to reduce antimicrobial usage in Korea.

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Ethics approval: Fecal samples were collected during routine veterinary examinations by licensed veterinarians for diagnostic purposes. As such, no experimental procedures were conducted on animals, and ethical approval by an Institutional Animal Care and Use Committee (IACUC) was not required.

Authors contribution: Suk-Kyung Lim, Hyun-Mi Kang, Kwang-Won Seo, and Wan-Kyu Lee conceived and planned the study. Kyung-Hyo Do, Su-Jin Choe, Chang Min Jung, and Seong-Won Lee carried out the experiment, performed and analysis and drafted manuscript. Kyung-Hyo Do wrote the manuscript in consultation with Kwang-Won Seo and Wan-Kyu Lee.

REFERENCES

Abubakar RH, Madoroba E, Adebowale O, *et al.,* 2019. Antimicrobial usage in pig production: Effects on *Escherichia coli* virulence profiles and antimicrobial resistance. Onderstepoort J Vet Res 86:1743.

Ager EO, Carvalho T, Silva EM, *et al.*, 2023. Global trends in antimicrobial resistance on organic and conventional farms. Sci Rep 13:22608.

Alarcón LV, Allepuz A and Mateu E, 2021. Biosecurity in pig farms: a review. Porc Heal Manag 7:5.

Andersen VD, Møller FD, Jensen MS, *et al.*, 2023. The quantitative effect of antimicrobial usage in Danish pig farms on the abundance of antimicrobial resistance genes in slaughter pigs. Prev Vet Med 214:105899.

EFSA, 2021. The European Union summary report on antimicrobial resistance in zoonotic and indicator bacteria from humans, animals and food in 2018/2019. EFSA J 19:e06490.

Caekebeke N, Jonquiere FJ, Ringenier M, *et al.*, 2020. Comparing farm biosecurity and antimicrobial use in high-antimicrobial-consuming broiler and pig farms in the Belgian–Dutch Border Region. Front Vet Sci 7:558455.

Caneschi A, Bardhi A, Barbarossa A, *et al.*, 2023. The use of antibiotics and antimicrobial resistance in veterinary medicine, a complex phenomenon: A narrative review. Antibiotics 12:487.

CLSI, 2023. Performance standards for antimicrobial susceptibility testing; twenty-fourth informational supplement.

Do KH, Byun JW and Lee WK, 2020a. Virulence genes and antimicrobial resistance of pathogenic *Escherichia coli* isolated from diarrheic weaned piglets in Korea. J Anim Sci Technol 62:543–52.

Do KH, Byun JW and Lee WK, 2020b. Antimicrobial resistance profiles of *Escherichia coli* from diarrheic weaned piglets after the ban on antibiotic growth promoters in feed. Antibiotics 9:755.

Garg S, Narwal KP and Kumar S, 2024. Economic sustainability of organic farming: an empirical study on farmer's prospective. Int J Sustain Agric Manag Inform 10:121–42.

Harlow M, Torremorell M, Rademacher CJ, *et al.*, 2024. Biosecurity insights from the United States swine health improvement plan: Analyzing data to enhance industry practices. Animals 14:1134.

Jung CM, Do KH and Seo K, 2023. Reduction in antimicrobial resistance prevalence in *Escherichia coli* and *Enterococcus* species from a swine farm in Korea following all-in/all-out management. J Bacteriol Virol 53:141–9.

Kidsley AK, Abraham S, Bell JM, *et al.*, 2018. Antimicrobial susceptibility of *Escherichia coli* and *Salmonella* spp. isolates from healthy pigs in Australia: Results of a pilot national survey. Front Microbiol 9:1207.

Lee YJ, 2023. Development of model to use antimicrobials in medically efficient way in broilers and pigs. Animal and Plant Quarantine Agency.

Maes DGD, Dewulf J, Piñeiro C, *et al.*, 2020. A critical reflection on intensive pork production with an emphasis on animal health and welfare. J Anim Sci 98:15–26.

Makovska I, Dhaka P, Chantziaras I, *et al.*, 2023. The role of wildlife and pests in the transmission of pathogenic agents to domestic pigs: a systematic review. Animals 13:1830.

Niemi JK, Sahlström L, Kyyrö J, *et al.*, 2016. Farm characteristics and perceptions regarding costs contribute to the adoption of biosecurity in Finnish pig and cattle farms. Rev Agric Food Environ Stud 97:215–23.

Pexas G and Kyriazakis I, 2023. Hotspots and bottlenecks for the enhancement of the environmental sustainability of pig systems, with emphasis on European pig systems. Porc Heal Manag 9:53.

Renault V, Humblet MF and Saegerman C, 2021. Biosecurity concept: origins, evolution and perspectives. Animals 12:63.

Seo KW, Do KH, Jung CM, *et al.*, 2023. Comparative genetic characterisation of third-generation cephalosporin-resistant *Escherichia coli* isolated from integrated and conventional pig farm in Korea. J Glob Antimicrob Resist 34:74–82.

Szymańska EJ, 2017. The Development of the pork market in the world in terms of globalization. J Agribus Rural Dev 16:843–50.

Wang L and Li D, 2024. Current status, challenges and prospects for pig production in Asia. Anim Biosci 37:742–54.

Wang J, Shi Z and Hu X, 2023. Status, evaluation, and influencing factors of biosecurity levels in pig farms in China. BMC Vet Res 19:272.

Yun J, Muurinen J, Nykäsenoja S, *et al.*, 2021. Antimicrobial use, biosecurity, herd characteristics, and antimicrobial resistance in indicator *Escherichia coli* in ten Finnish pig farms. Prev Vet Med 193:105408.