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WASH-BIOSECURITY INTERVENTION STRATEGIES TO REDUCE *E. COLI* AND ESBL *E. COLI* EXPOSURE IN FARMWORKERS

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ABSTRACT

Introduction *E. coli* and extended-spectrum β-lactamase-producing *E. coli* in livestock farming represent a significant occupational health risk to farmworkers. To evaluate potential mitigation strategies within a *One Health* framework, this study applied a Quantitative Microbial Risk Assessment at a teaching farm in Indonesia.

Materials and methods The assessment examined the effects of various *WASH-biosecurity* interventions, including feed silo installation, the use of semi-automatic manure scrapers and conveyors, and modifications to composting practices, by using a Monte Carlo simulation to estimate the potential exposure reduction.

Results The interventions showed variable effectiveness. Modifying the ruminant composting house with porous concrete was the most effective approach, reducing *E. coli* exposure by approximately 99%. The installation of semi-automatic scrapers for ruminant manure and feed silos also proved highly effective, resulting in reductions of 88.3% and 87.6%, respectively.

Conclusions The study concluded that targeted source-specific WASH-biosecurity strategies, particularly improvements to ruminant composting infrastructure, are crucial for significantly reducing microbial exposure and protecting the health of farmworkers from antimicrobial resistance-related risks.

Keywords *E. coli*, Indonesia, intervention scenario, livestock, occupational health.

STRATEGII DE INTERVENȚIE WASH PENTRU A REDUCE EXPUNEREA LA *E. COLI* ȘI *E. COLI* PRODUCĂTOARE DE ESBL LA LUCRĂTORII DIN FERME

Introducere *E. coli* și *E. coli* producătoare de β-lactamaze cu spectru extins (ESBL) reprezintă agenți patogeni relevanți în fermele zootehnice, constituind un risc major pentru sănătatea lucrătorilor agricoli. Pentru a evalua strategiile de reducere a riscului în cadrul conceptului *One Health*, prezentul studiu a apelat la o estimare cantitativă a riscului microbian într-o fermă didactică din Indonezia.

Materiale și metode Evaluarea a modelat impactul diferitelor intervenții *WASH-biosecuritate*, inclusiv instalarea de silozuri pentru furaje, utilizarea de raclete semiautomate pentru gunoiul de grajd și benzi transportoare, precum și modificări ale procesului de compostare, folosind o simulare Monte Carlo pentru a analiza potențialele reduceri ale expunerii.

Rezultate Studiul a demonstrat eficiențe variate între intervențiile evaluate. Modificarea adăpostului de compostare pentru rumegătoare cu beton poros a reprezentat cea mai eficientă strategie, reducând expunerea la E. coli cu aproximativ 99%. Instalarea de raclete semiautomate pentru gunoiul de grajd de la rumegătoare și silozurile pentru furaje au fost, de asemenea, foarte eficiente, contribuind la reduceri de 88,3% și 87,6%, respectiv.

Concluzii Studiul a relevat că strategiile *WASH-biosecuritate*, direcționate și specifice sursei, în special îmbunătățirile infrastructurii de compostare pentru rumegătoare, sunt esențiale pentru reducerea semnificativă a expunerii microbiene și protejarea sănătății lucrătorilor din ferme împotriva amenințării rezistenței antimicrobiene.

Cuvinte-cheie *E. coli*, Indonezia, scenariu de intervenție, animale de fermă, sănătatea ocupațională.

INTRODUCTION

ESBL *E. coli* refers to strains of *E. coli* that produce an enzyme called β-lactamase, making it resistant to various β-lactam antibiotics, including penicillins and cephalosporins (1). As antimicrobial-resistant strains, these organisms can thrive in a variety of environmental reservoirs. Their presence complicates the treatment of infection and has been detected in soil, water, and ambient air within farm environments. Such resistance is a potential threat to animal health and increases the risk of occupational exposure among farmworkers who are in daily contact with livestock and contaminated surroundings. Consequently, this may contribute to development of urinary tract infections, respiratory tract infections, and sepsis (2).

Direct contact with animal feces is a key transmission route for both *E. coli* and ESBL-producing *E. coli*, with beef cattle stool posing the highest modelled infection risk (9.8×10^{-3} pppy) due to concentrations of up to 2.49 $\log_{10}$ CFU/gram and seasonal ingestion rates of 6.84–8.64 mg/day (3). ESBL *E. coli* exposure affected 12% of livestock workers and up to 43% of farming communities, with ingestion responsible for 90% of colonization, which highlights the urgent need for targeted interventions (4–6).

The One Health approach integrates human, animal, and environmental health to address issues such as exposure to *E. coli* and ESBL *E. coli*. Within this framework, the WASH-biosecurity intervention model is particularly relevant to occupational health, as it combines water, sanitation, and hygiene (WASH) measures with biosecurity practices. The WASH-biosecurity strategy in livestock settings was initially introduced by Jimenez *et al.* and later developed into a comprehensive framework (7,8).

The WASH program focuses on providing clean water, adequate sanitation facilities, and promoting hygiene practices to reduce the spread of *E. coli* and ESBL *E. coli* (9). Biosecurity measures, including restricted access to livestock areas, routine disinfection procedures, and livestock vaccination, further contribute to reducing transmission of *E. coli* and ESBL *E. coli* (10). By combining these strategies, the One Health approach is expected to reduce *E. coli* and ESBL *E. coli* exposure in farming communities and protect both human and animal health from its adverse effects.

This study employed a Quantitative Microbial Risk Assessment (QMRA) framework to analyze the exposure of *E. coli* and ESBL *E. coli* in ruminant and poultry areas at the Teaching Factory (TEFA). ESBL *E. coli* concentrations were determined through systematic sampling and laboratory analysis conducted between November 2023 and July 2024 in livestock areas within the TEFA facility in Sukabumi City, West Java Province, Indonesia. *E. coli* was used as a fecal indicator organism to assess environmental contamination, while ESBL-producing *E. coli* was treated as an antimicrobial resistance (AMR) outcome with direct implications for occupational health. Additionally, fecal ingestion rates were estimated by analyzing incidental fecal-oral exposure pathways among farmworkers (3). The QMRA results and fecal ingestion rates were used to assess infection risks and guide targeted interventions for farmworker safety.

This study aimed to assess exposure using a One Health approach and a WASH-biosecurity strategy. The proposed interventions were tailored to priority groups, including poultry and ruminant farmworkers. The intervention scenarios were designed to reduce levels of *E. coli* and ESBL *E. coli* in livestock environments compared to baseline concentrations. This decrease in microbial levels, along with reduced ingestion rates, was expected to decrease overall exposure among farmworkers. Identification of the most promising WASH-biosecurity strategies, based on their effectiveness in reducing exposure to *E. coli* and ESBL *E. coli*, was considered a key outcome of the study.

MATERIALS AND METHODS

This study addressed not only ESBL *E. coli* but also *E. coli* more broadly. This approach is supported by previous research on WASH and biosecurity interventions, which has predominantly targeted the reduction or elimination of *E. coli* in the environment. In the present study, *E. coli* was considered a fecal indicator bacterium and a proxy for potential exposure to enteric pathogens.

Exposure of *E. coli* and ESBL *E. coli*

Data on the occurrence of *E. coli* and ESBL *E. coli* were obtained from previous analyses conducted at TEFA in Sukabumi. The study site includes various livestock facilities, such as broiler chicken farms, poultry farms (including ducks, quails, and layer chickens), cattle farms, and small ruminant farms. Only sampling points with high concentrations of *E. coli* and ESBL *E. coli* (Table 1), namely: (1) broiler and duck stools; (2) poultry- and cattle-derived fertilizers; and (3) concentrated feed for broilers, ducks, and cattle were selected for intervention-based exposure reduction analysis. Subsequently, the fecal ingestion rates, together with other relevant variables (Table 1) and the concentrations of E. coli and ESBL E. coli, were used to estimate exposure at each sampling point using the following QMRA equations:

Exposure due to farmworker contact with livestock stools (11),

$$C_{stool} = IR_{fecal} \times Conc_{Ec\_stool/ESBL\ Ec\_stool} \quad (1)$$

where C_{stool} represents the exposure resulting from worker contact with feces ($\log_{10}$ CFU/day), IR_{fecal} denotes the fecal ingestion rate (mg/day), and $Conc_{Ec\_stool}$/$ConcESBL_{Ec\_stool}$ refers to the concentrations of *E. coli* and ESBL *E. coli* derived from fecal samples ($\log_{10}$ CFU). The IR_{fecal} value was further adjusted based on location, specifically whether the exposure occurred at a ruminant or poultry farm and was derived from previous studies conducted at the same sites.

Exposure due to worker contact with livestock feed (12),

$$C_{feed} = IR_{feed} \times Conc_{Ec\_feed} \quad (2)$$

where C_{feed} is the exposure due to worker contact with livestock feed ($\log_{10}$CFU/day), IR_{fecal} is the ingestion rate (mg/day), and $Conc_{Ec\_feed}$ is the concentration of *E. coli* in livestock feed samples ($\log_{10}$ CFU).

Exposure due to worker contact during the application of fertilizer to soil (13),

$$C_{fertilizer} = IR_{fertilizer} \times Conc_{Ec\_fertilizer} \times 10^{-(k.t)} \quad (3)$$

where $C_{fertilizer}$ is the exposure due to worker contact with fertilizer ($\log_{10}$ CFU/day), $IR_{fertilizer}$ is the ingestion rate (mg/day), $Conc_{Ec\_fertilizer/ESBL\ Ec\_fertilizer}$ is the concentration of *E. coli* in fertilizer samples ($\log_{10}$ CFU), k is the decay kinetics of *E. coli* per day ($\log_{10}$/day), and t is the time between fertilizer application to the field and exposure, ranging from 0 to 30 days. Exposure was assumed to occur 30 days after fertilizer application.

The magnitude of exposure to *E. coli* and ESBL *E. coli* depended on the independent and dependent variables presented in Table 1. Concentration data for livestock stools, feed, and livestock fertilizer were derived from previously conducted unpublished primary research.

Table 1. The variables used to calculate exposure to *E. coli* and ESBL *E. coli* in this study.

Mathematical Formula / Variable	Description	Distribution & Parameters	Source
Ingestion Rate (IR) of Non-fecal Source			
Feed source (IR_{feed}) (mg/day)	Analogous to soil volume accidentally ingested during transport of soil-filled sacks	Uniform: Min = 32, Max = 42.5	(14,15)
Fertilizer source ($IR_{fertilizer}$) (mg/day)	-	Uniform: Max. = 480, Min. = 50	(13)
Ingestion Rate (IR) of Fecal Source			
Ruminant stools (IR_{fecal}) (mg/day)	-	Log normal: Average = 6.84, Min. = 1.26, Std. dev.= 6.22	(3)
Poultry stools (IR_{fecal}) (mg/day)	-	Weibull: Scale = 0.45, Shape = 0.8, Location = 0	(3)
Concentrations			
$Conc_{Ec\_stool}$ (log_{10} CFU)	Concentration of *E. coli* in cattle and small ruminant stool	Log-normal: *E. coli* in cattle Mean = 3.79, SD = 0.44, Min = 2.95; *E. coli* in small ruminant Mean = 3.15, SD = 0.26, Min = 2.95	Primary data
$Conc_{Ec\_feed}$ (log_{10} CFU)	Concentration of *E. coli* in feed	Log-normal: Mean = 7.40, SD = 0.04, Min = 7.37	Primary data
$Conc_{Ec\_fertilizer}$ (log_{10} CFU)	Concentration of *E. coli* in fertilizer	Log-normal: Mean = 5.3, SD = 1.2, Min = 3.0	Primary data
$Conc_{Ec\_stool/ESBL\ Ec\_stool}$ (log_{10} CFU)	Concentration of *E. coli* and ESBL *E. coli* in broiler and duck stool	Log-normal: *E.coli* in broiler Mean = 7.82, SD = 0.60, Min = 6.60; *E. coli* in duck Mean = 6.25, SD = 1.77, Min = 2.95; ESBL *E. coli* in broiler Mean = 7.48, SD = 7.80, Min = 4.23; ESBL *E. coli* in duck Mean = 4.95, SD = 5.09, Min = 3.13	Primary data
$Conc_{Ec\_feed}$ (log_{10} CFU)	Concentration of *E. coli* in feed	Log-normal: *E. coli* in broiler Mean = 6.95, SD = 1.88, Min = 4.78; *E. coli* in duck Mean = 6.99, SD = 0.46, Min = 6.30	Primary data
$Conc_{Ec\_fertilizer}$ (log_{10} CFU)	Concentration of *E. coli* in fertilizer	Log-normal: Mean = 6.3, SD = 1.6, Min = 3.3	Primary data
The Other Parameters and Distributions			
Decay kinetics of *E. coli* (k) (log_{10}/day)	Die-off rate of *E. coli*	PERT: Min = 0.041, Most likely = 0.05, Max = 0.0625	(13)
Recovery factor (RF) of *E. coli*	Recovery efficiency of *E. coli*	Uniform: Min = 50%, Max = 90%	(16)
Time interval after fertilizer application (t) (day)	After fertilizer application	Uniform: Min = 0, Max = 30	(17)

Exposure Reduction and Sensitivity Analysis

Efforts to reduce exposure to *E. coli* and ESBL *E. coli* were focused on WASH-biosecurity intervention scenarios directed at critical exposure sources posing a high risk to livestock workers. Once the intervention-modified variables had been identified, exposure was recalculated to estimate the percentage reduction. A Monte Carlo simulation (10,000 iterations, Oracle Crystal Ball v.11) was used to quantify the contribution of each input parameter to output variance. One source of uncertainty was the use of literature-based fertilizer ingestion rates.

RESULTS

Magnitude of *E. coli* and ESBL *E. coli* Exposure and Intervention Scenario

Exposure to *E. coli* and ESBL *E. coli* varied widely across sources. For *E. coli*, the highest median was from poultry fertilizer (6,139 $\log_{10}$ CFU/day), followed by cattle fertilizer (2,474 $\log_{10}$ CFU/day). Ruminant feed (median: 275 $\log_{10}$ CFU/day) exceeded poultry feed (median: 240 $\log_{10}$ CFU/day). Cattle and small ruminant stools (median: 17 $\log_{10}$ CFU/day) surpassed poultry stools (median: 2 $\log_{10}$ CFU/day). For ESBL *E. coli*, poultry fertilizer showed the highest exposure (median: 5,290 $\log_{10}$ CFU/day), followed by cattle fertilizer (median: 304 $\log_{10}$ CFU/day). Broiler feed (median: 220 $\log_{10}$ CFU/day) exceeded other feed types (median: 129 $\log_{10}$ CFU/day). Cattle and small ruminant stools (median: 11 $\log_{10}$ CFU/day) had higher exposure than poultry stools (median: 1 $\log_{10}$ CFU/day). Overall, fertilizers contributed the greatest exposure, followed by feed and stools.

The intervention scenario aimed at reducing exposure to *E. coli* and ESBL *E. coli* was divided into two categories based on the receptor: workers on ruminant and poultry farms. One study found that optimizing C:N ratio and moisture during poultry manure composting reduced ESBL *E. coli* by up to 2 $\log_{10}$ CFU (18). Details of these scenarios, together with the magnitude of reduction achieved through approaches targeting either *E. coli* concentration, ESBL *E. coli* concentration, or the ingestion rate, are presented in Table 2. The ingestion-rate reduction scenario was based on the installation of semi-automatic scrapers and conveyors, which may reduce both the duration of work and the amount of fertilizer material inadvertently ingested by farmworkers by approximately 50% (19).

Table 2. Intervention scenarios for reducing exposure to *E. coli* or ESBL *E. coli* among workers in TEFA.

Target Group	Exposure Source	Intervention	Modified Variable	Modified Variable	Source
Farmworkers on Ruminant Farms	Livestock Feed	Installation of feed storage silos	*E. coli* concentration	Reduction of 5 – 7 $\log_{10}$ CFU	(20)
	Ruminant Stools	Modification of ruminant composting house	*E. coli* concentration	~99% reduction	(21)
	Ruminant Fertilizer	Installation of semi-automatic scrapers	Ingestion rate	50% reduction	(19)
Farmworker in Poultry Farms	Livestock Feed	Installation of feed storage silos	*E. coli* concentration	Reduction of 5 – 7 $\log_{10}$ CFU	(20)
	Poultry Stools	Optimization of poultry composting process	ESBL *E. coli* concentration	Reduction of ~2$\log_{10}$ CFU	(18)
	Poultry Fertilizer	Installation of semi-automatic conveyor	Ingestion rate	50% reduction	(19)

The highest exposure levels of *E. coli* were observed in poultry fertilizer and broiler feed. ESBL *E. coli* followed similar exposure pathways in poultry fertilizer and the handling of poultry stools. While exposure via livestock feed and fertilizers can be mitigated through the implementation of storage silos and semi-automatic transport systems, the reduction of fecal exposure requires highly specific, source-oriented interventions. Within the integrated WASH-biosecurity framework, the use of feed silos aligns with hygiene-biosecurity protocols, semi-automatic transport systems under sanitation measures and fecal exposure mitigation represents a combined sanitation-biosecurity approach.

Mitigating *E. coli* Exposure from Livestock Feed and Fertilizer

Feed Storage Silo Installation

Under baseline conditions, without intervention (Figure 1), *E. coli* exposure from livestock feed varied by feed type. Broiler feed showed the highest exposure levels, reaching up to 500 $\log_{10}$ CFU/day. In contrast, non-broiler poultry feed exposure ranged from 0 to 400 $\log_{10}$ CFU/day, with peak probabilities concentrated between 100 and 300 $\log_{10}$ CFU/day. Ruminant feed exhibited a lower exposure profile, ranging from 0 to 250 $\log_{10}$ CFU/day and peaking between 150 and 200 $\log_{10}$ CFU/day. According to this study, installing feed storage silos reduced worker exposure during daily feed handling. The highest efficiency was observed for broiler feed, with an exposure reduction of 87.6% (95% CI: 85.6–89.6%), followed by non-broiler poultry feed at 85.8% (95% CI: 83.6–88.0%) and ruminant feed at 81.1% (95% CI: 78.7–83.5%).

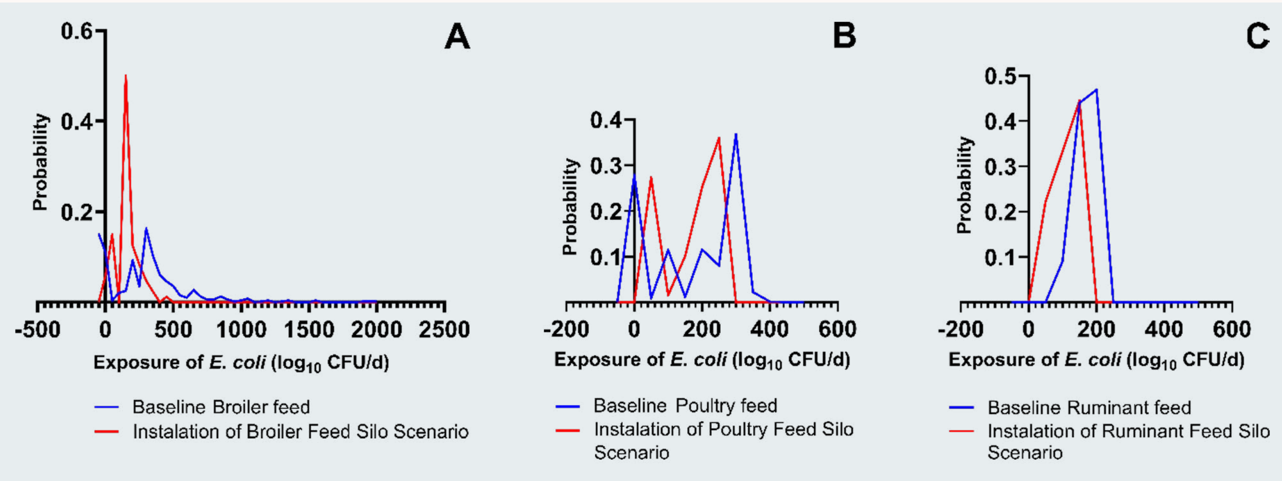

Figure 1. Comparison of *E. coli* exposure in livestock feed stored in silos. The feed sources included broilers (A), non-broiler poultry (B), and ruminants (C). The comparison included the baseline conditions (blue) and feed silo installation scenario (red). (A) Broiler feed: The baseline showed a broad distribution exceeding 500 $\log_{10}$ CFU/day, with a peak probability of 0.17. After the silo installation, the exposure was markedly reduced, with the peak probability rising to 0.50 (at 100 $\log_{10}$ CFU/day).

(B) Non-broiler poultry feed: Baseline ranges 0–400 $\log_{10}$ CFU/day with peak 0.37 (at 300 $\log_{10}$ CFU/day); post-silo, the peak shifts to 0.36 (at 250 $\log_{10}$ CFU/day). (C) Ruminant feed: Baseline ranges 0–250 $\log_{10}$ CFU/day with peak 0.47 (at 200 $\log_{10}$ CFU/day); after silo, the peak shifts to 0.44 (at 150 $\log_{10}$ CFU/day).

The x-axis depicted the *E. coli* exposure levels, and the y-axis indicated the probability of exposure. The x-axis is represented in $\log_{10}$ CFU/d (d = day), while the y-axis illustrated the probability (0-1).

Installation of Semi-automatic Scrapers and Conveyors

The installation of scrapers for ruminant manure and conveyors for poultry manure significantly reduced the risk of *E. coli* exposure relative to baseline conditions (Figure 2). Under baseline scenarios, exposure to ruminant fertilizer showed a broader distribution, with daily estimates ranging from 10^3 to 10^4 $\log_{10}$ CFU/day. The 50% scraper scenario reduced *E. coli* exposure to undetectable logarithmic levels, corresponding to a reduction efficiency of 88.3% (95% CI: 86.3–90.3%). In contrast, poultry fertilizer showed higher baseline exposure, reaching up to 1.5×10^4 $\log_{10}$ CFU/day. The 50% conveyor scenario achieved a 56.1% reduction (95% CI: 53.0–59.2%), with the highest probability observed at the lowest exposure level of approximately 10^3 $\log_{10}$ CFU/day.

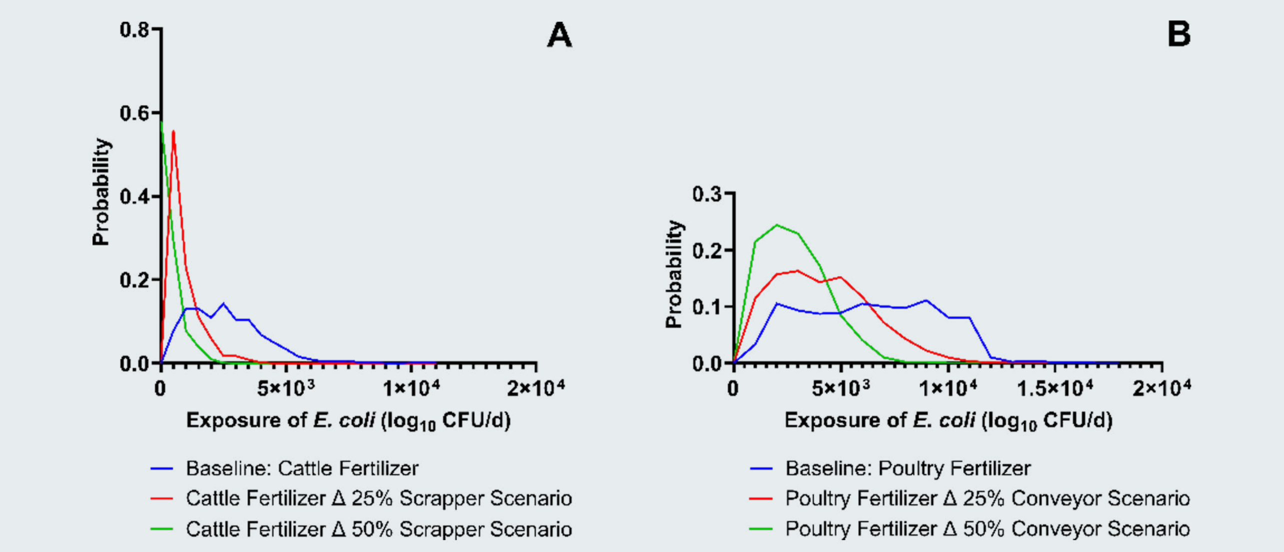

Figure 2. Comparison graph of *E. coli* exposure following the installation of scrapers and conveyors for manure handling. The manure sources included ruminants (A) and poultry (B). The comparison included baseline conditions (blue), a 25% ingestion reduction scenario (red), and a 50% ingestion reduction scenario (green).

(A) Ruminant fertilizer (cattle): The baseline exposure was broadly distributed between 10^3 and 10^4 $\log_{10}$ CFU/day. The 25% scraper narrowed the distribution and shifted the peak probability to 0.55 at much lower exposures (< 10^3 $\log_{10}$ CFU/day). The 50% scraper further reduced exposure to undetectable logarithmic levels, and the peak probability moved close to zero exposure.

(B) Poultry fertilizer: Baseline exposure reached up to 1.5×10^4 $\log_{10}$ CFU/day. The 25% conveyor reduced the maximum exposure and increased the peak probability to 0.16 at lower exposure levels. The 50% conveyor shifted the distribution further left, increasing the peak probability to 0.24 at much lower exposures. The x-axis depicted the *E. coli* exposure level, and the y-axis indicated the probability of exposure. The x-axis is represented in $\log_{10}$ CFU/d (d = day), while the y-axis illustrated the probability (0-1).

Mitigation of *E. coli* and ESBL *E. coli* Exposure from Ruminant and Poultry Fecal Sources

Optimization of the Poultry Composting Process

For broiler stools, the highest probability of exposure to ESBL *E. coli* was 0.3 at 2 $\log_{10}$ CFU/day, decreasing sharply as exposure levels increased to 40 $\log_{10}$ CFU/day (Figure 3). Composting reduced this probability to 0.2 at the same exposure level, with further reductions observed up to 30 $\log_{10}$ CFU/day. For non-broiler stools, the highest probability was 0.2 at 2 $\log_{10}$ CFU/day and decreased to zero at 30 $\log_{10}$ CFU/day. Under the composting mitigation scenario, non-broiler stools showed a peak probability of 0.3 between 2 and 4 $\log_{10}$ CFU/day, with the exposure range decreasing to 28 $\log_{10}$ CFU/day. Optimization of the composting process was more effective for non-broiler stools (63%; 95% CI: 60–66%) than for broiler stools (40.2%; 95% CI: 37.2–43.2%).

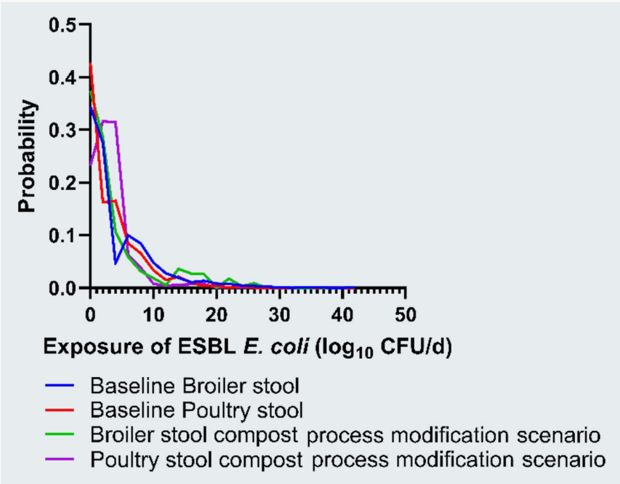

Figure 3. Comparison graph of ESBL *E. coli* exposure following composting process modifications in poultry farming areas. Baseline broiler stools are represented in blue, baseline non-broiler poultry stools in red, modified composting scenario for broiler stools in green, and modified composting scenario for non-broiler poultry stools in purple. For broiler stools (blue), the highest exposure probability is 0.3 at 2 $\log_{10}$ CFU/day, then falls sharply as the exposure increases to 40 $\log_{10}$ CFU/day. The composting scenario (green) reduced the peak probability to 0.2 at the same exposure level and contracted the maximum exposure range to 30 $\log_{10}$ CFU/day. For non-broiler poultry stools, the baseline (red) peak probability was 0.2 at 2 $\log_{10}$ CFU/day, reaching zero at 30 $\log_{10}$ CFU/day. After composting mitigation (purple), the peak rose to 0.3 across 2–4 $\log_{10}$ CFU/day, whereas the maximum exposure range decreased to 28 $\log_{10}$ CFU/day. The x-axis is represented in $\log_{10}$ CFU/d (d = day), while the y-axis is illustrated the probability of exposure (0-1).

Modification of Ruminant Composting House

Baseline *E. coli* exposure from cattle stools showed a probability of 0.3 at an exposure level of 1 $\log_{10}$ CFU/day, which decreased to approximately 7×10^{-2} at 4 $\log_{10}$ CFU/day and approached zero at higher exposure levels (Figure 4). Modification of the composting facility with porous concrete resulted in a reduction efficiency of up to 99% (95% CI: 98.4–99.6%). In small ruminant stools, the baseline scenario showed the highest exposure probability of 0.5 at 1 $\log_{10}$ CFU/day, which dropped sharply to approximately 5×10^{-2} at exposure levels above 4 $\log_{10}$ CFU/day. The porous concrete intervention in small ruminant composting facilities also showed the same reduction efficiency of 99% (95% CI: 98.4–99.6%).

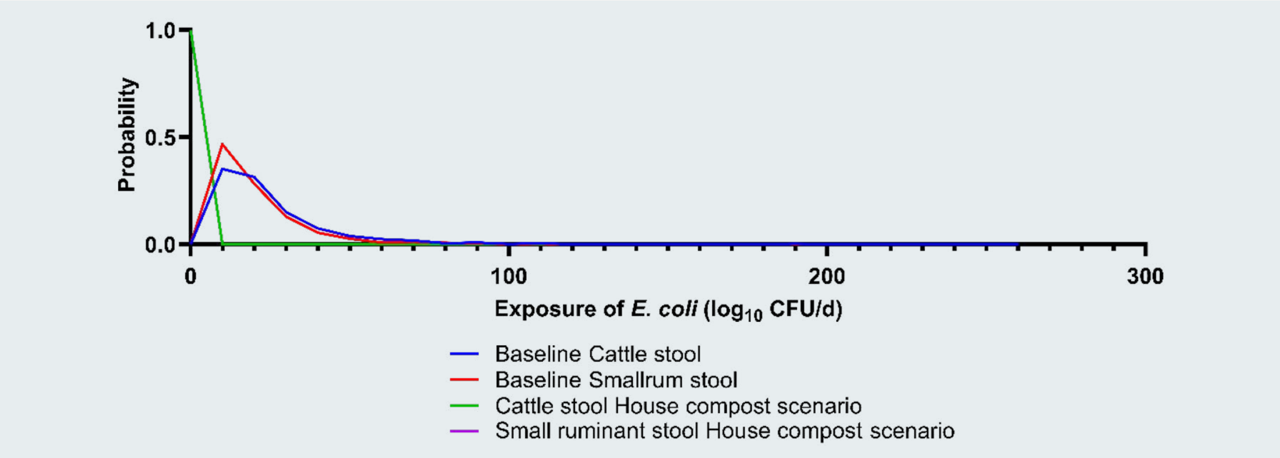

Figure 4. Comparison of *E. coli* exposure following the construction of composting facilities using porous concrete in ruminant farming areas. Baseline cattle stools are represented in blue, baseline small ruminant stools in red, the intervention scenario for cattle composting facilities in green, and the intervention scenario for small ruminant composting facilities in purple. For cattle stool (blue), the baseline exposure probability was 0.3 at 1 $\log_{10}$ CFU/day, falling to 7×10^{-2} at 4 $\log_{10}$ CFU/day, and approaching zero at higher exposures. For small ruminant stool (red), the peak probability was 0.5 at 1 $\log_{10}$ CFU/day, dropping to 5×10^{-2} above 4 $\log_{10}$ CFU/day. The porous concrete modification (green and purple curves) showed probabilities rising to 1.0 near zero exposure. The x-axis represented the *E. coli* exposure levels in $\log_{10}$ CFU/d (d = day), while the y-axis indicated the probability of exposure.

DISCUSSION

Sources of Exposure

This study elucidated two distinct yet complementary dimensions of microbial exposure within livestock environments. The study found that exposure to *E. coli* was consistently higher in fertilizers and livestock feed than in stools, challenging the conventional assumption that animal feces are the primary source of microbial risk. As a fecal indicator organism, *E. coli* reflects general hygiene and sanitation conditions, and its elevated levels in fertilizers and feed suggest that suboptimal composting practices and nutrient-rich substrates can amplify microbial concentrations. Furthermore, cross-contamination during feed storage further elevates exposure, underscoring vulnerabilities in current farm hygiene management (22). In contrast, ESBL-*E. coli* served as an antimicrobial resistance (AMR) endpoint. Its presence in fertilizers resulted in significantly lower peak exposure levels compared to general *E. coli*, with more pronounced reduction efficacy observed in non-broiler manure than in broiler-derived samples. These findings highlight occupational health risks that extend beyond environmental contamination. The risk of ingestion is further heightened by frequent and prolonged worker contact during routine cleaning and animal handling, emphasizing the necessity of stringent occupational hygiene protocols (3,23).

Effectiveness of Intervention Scenarios

A simplified intervention scenario involving the installation of scrapers and conveyor systems may provide an effective strategy for mitigating future *E. coli* exposure risks. This approach is based on the physical characteristics of the fertilizer, the concentration of *E. coli* present, and the ingestion rates. Poultry fertilizer, characterized by its high moisture content, low density, and minimal fibre content, is more compatible with conveyor belt systems (24). Conversely, ruminant manure—which tends to be denser and possesses a higher fiber content—is more effectively managed through the use of mechanical scrapers (25). Although poultry manure exhibits higher exposure levels, its response to mitigation using conveyor systems is limited. This may be attributed to the fact that conveyor installations often involve open-system transport, which maintains the potential for worker contact with contaminated surfaces. In contrast, mechanical scrapers demonstrate superior efficacy by providing direct, systemic removal of manure from floor surfaces, thereby minimizing the duration and surface area of environmental exposure that serves as a potential source of contamination.

The reduction of *ESBL E. coli* exposure was greater in non-broiler fertilizer (63%) than in broiler fertilizer (40%) owing to its lower nutrient content, which led to more controlled microbial activity and faster temperature increase during composting, thereby accelerating the degradation of *ESBL E. coli* (18). Consequently, characterizing the physicochemical composition of poultry feces prior to composting is essential for optimizing interventions and understanding differential exposure risks across different poultry types.

Furthermore, the installation of porous concrete as a composting house material significantly reduced *E. coli* exposure. High concrete porosity increases fluid permeability, allowing better airflow and water movement, which supports the organic matter (26). The size and distribution of pores also influence microbial interactions with concrete, and larger and interconnected pores provide better habitats for microbes. However, high porosity can reduce the resistance of concrete to acidic environments, accelerating material degradation and potentially compromising long-term structural durability (27). The use of acid-resistant protective layers may therefore help preserve composting performance while maintaining structural stability.

Field testing is necessary to confirm the effectiveness of livestock feed silos, scrapers, conveyor installations, optimized manure composting, and the use of porous concrete under various geographic and climatic conditions. Environmental variability, such as temperature, humidity, rainfall, and soil conditions, can influence the effectiveness of these interventions in reducing *E. coli* exposure, particularly that of ESBL *E. coli*.

Future Directions

Efforts to reduce exposure to *E. coli* and *ESBL E. coli* have produced mixed outcomes across different farm types. Interventions on ruminant farms have shown promising results, indicating a strong potential to improve health indicators in these settings. However, poultry farms present distinct operational and microbial challenges, such as higher microbial loads and more intensive management practices, which may limit the effectiveness of standard approaches. Future research should investigate the integration of various sanitation technologies to improve the efficiency of ESBL *E. coli* exposure reduction.

CONCLUSIONS

1. Targeted WASH-biosecurity actions have been highly effective in reducing *E. coli* and ESBL *E. coli* among farmworkers. Their success depends on the method used and the type of livestock.
2. The most effective method was changing the ruminant composting area to porous concrete, which reduced *E. coli* exposure by approximately 99%.
3. Other effective methods for ruminant farms included:
   a. Semi-automatic manure scrapers (88.3% reduction)
   b. Feed silos (87.6% reduction)
4. In poultry farms, the interventions were also helpful but showed weaker results compared to ruminant farms.
5. This study provides clear guidance on prioritizing interventions within a One Health framework.

CONFLICT OF INTEREST

Nothing to declare.

CONTRIBUTIONS

Y. V. Paramitadevi conducted the data analysis, drafted the manuscript, and managed the study. F. Marcelita handled data simulations. I. Rahmatika designed the methodology. C. R. Priadi verified the simulation data, reviewed the manuscript, and supervised the research. A. Ristianingrum and A. Rukmana contributed to the investigation and provided subject-specific insights. N. Suwartha reviewed and supervised the study. S. K. Saptomo supported simulations and secured funding.

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ETHICAL APPROVAL

This study did not involve human participants or livestock. Ethical approval was not required according to the current institutional and national guidelines.

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