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SUSTAINABILITY ASSESSMENT OF PHYTOBIOTIC FEED ADDITIVES IN POULTRY FARMING: A CASE FROM SOUTH SULAWESI, INDONESIA

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ABSTRACT

South Sulawesi, Indonesia, has emerged as a testing ground for phytobiotic feed additives (PFAs) adopted in response to the 2018 national ban on in feed antibiotic growth promoters. Up to now system-wide sustainability evidence remains fragmentary. Using a modified Rapid Appraisal for Fisheries (RAPFISH) protocol termed RAPPhytoFeed, 60 stakeholders (farmers, extension agents, feed mill representatives, policy makers, and academics) across four high density poultry districts were participated in the present study. Multidimensional scaling ordination produced sustainability indices for five dimensions: ecology (77.7 ± 0.5), economy (62.3 ± 0.1), social (56.5 ± 0.5), technology (55.0 ± 0.3), and institution (49.6 ± 0.0). Monte Carlo stress values (<0.075) and R^2>0.96 confirmed ordination stabilsystemity. Leverage analysis showed feed conversion ratio efficiency, wastewater quality, local raw material access, trained workforce, and policy support as the most influential attributes. While ecological and economic gains are recognised, low institutional readiness and uneven technical capacity constrain broader uptake. We conclude that Indonesia's antibiotic-free poultry transition will hinge on coordinated investment in laboratory services, farmer training, and market incentives for AGP-free meat. The RAPPhytoFeed tool offers a rapid, stakeholder-centred lens that can be replicated in other emerging livestock hotspots to guide policy and private-sector decisions on phytobiotic scale-out.

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INTRODUCTION

Poultry is the fastest growing livestock subsector in Indonesia, mirroring a global trend driven by the rising demand for affordable animal protein (Paramayudha and Budhisatrio, 2024; Sumiati *et al*., 2025). However, the conventional reliance on in-feed antibiotic growth promoters (AGPs) to sustain high productivity has come under increasing scrutiny, primarily due to their role in accelerating antimicrobial resistance (AMR) in both animal and human pathogens (Manyi-Loh *et al*., 2018). Beyond AMR, intensive poultry farming is also associated with broader environmental and public health burdens, including emissions of ammonia, nitrous oxide, and methane; contamination of soil and water with antibiotics, hormones, and pathogens; and negative health effects on farm workers and surrounding communities (Gržinić *et al*., 2023).

Following the European Union's 2006 AGP ban (Moyane *et al*., 2013; Millet and Maertens, 2011), several countries including Indonesia, which officially banned AGPs in 2018 have strengthened regulations on antibiotic use in livestock production (Sumiati *et al*., 2025). This regulatory shift compels producers to seek natural, effective, and economically viable alternatives that can maintain animal health and production efficiency without compromising public or environmental safety.

Phytobiotic feed additives, herbs, spices, essential oils and oleoresins rich in phenolics, terpenoids and other secondary plant metabolites, and have emerged as leading AGP substitutes *(*Boukhary *et al.,* 2019*;* Ivanova *et al.,* 2024*;* Obianwuna *et al*., 2024). These functional traits contribute to improved gut health, nutrient absorption, and overall resilience in poultry. Experimental findings indicate that phytobiotics can modulate gut microbiota composition, enhance mucosal immunity, and increase feed efficiency, particularly when combined with beneficial microbes such as *Clostridium butyricum* or probiotics like *Lactobacillus spp.* (Hashem *et al*., 2022; Liang *et al*., 2021). Beyond physiological effects, phytobiotics also support carcass quality and market value. Dietary supplementation with turmeric extract and garlic extract, as well as their combination, significantly enhance water holding capacity and sensory acceptability in broiler meat without negatively affecting other physical parameters (Purwanti *et al*., 2019). Additives such as *Origanum vulgare* and *Citrus sinensis* have demonstrated improvements in oxidative stability, meat flavor, and antioxidant status, suggesting that phytobiotics may serve as premium enhancers of poultry product quality (Abd El-Hack *et al*., 2022; Ren *et al*., 2019). For animal metabolic health, Indigofera, and turmeric in the diet of native chickens significantly improved lipid regulation and cardiovascular biomarkers, including reductions in LDL, triglycerides, and NEFA levels, along with increased HDL and adiponectin (Purwanti *et al*., 2024).

Despite promising evidence, field-level outcomes remain highly variable and context-dependent, influenced by botanical source, dosage, bird genotype, and diet interactions (Abdelli *et al*., 2021; Krauze, 2021). Recent reviews nevertheless highlight wide performance variability that depends on botanical source, extraction method, inclusion rate, bird genotype and background diet (Abdelli *et al*., 2021; Wang *et al*., 2024). As a result, there is still limited consensus on how, and under what production conditions, phytobiotics translate into truly sustainable poultry systems. Moreover, most existing studies in Indonesia focus narrowly on zootechnical parameters such as growth rate, feed conversion ratio, or cost benefit analysis, without capturing the broader sustainability implications across environmental, social, and institutional dimensions. As a result, there is limited understanding of how phytobiotic interventions interact with farm scale realities such as waste management practices, labor knowledge gaps, market access, and regulatory compliance. This analytical gap constrains the ability of policy makers, nutritionists, and producers to assess the long-term viability and systemic trade off of phytobiotic adoption. A recent review by (Aminullah *et al*., 2025) emphasizes that sustainability evaluations in Indonesian poultry systems often remain fragmented, lacking multidimensional frameworks that integrate ecological performance with social acceptance and institutional support.

South Sulawesi province is one of Indonesia's principal broiler and layer hubs (Ian, 2014; Suganda *et al*., 2024), hosting a mosaic of smallholder and commercial operations that increasingly experiment with phytogenic additives (Astuti *et al*., 2023; Hamid *et al*., 2025). Yet, published data on the multidimensional sustainability of these practices, balancing productivity gains with economic resilience, environmental stewardship and social acceptability remain scant. Most Indonesian studies focus narrowly on short term zootechnical responses or cost–benefit ratios and rarely adopt an integrated sustainability lens (Aminullah *et al*., 2025). Consequently, policy makers and feed formulators alike lack context specific evidence to scale phytobiotic strategies confidently.

Despite growing interest in phytobiotic based poultry production, there has been insufficient attention to the sustainability implications of these practices. Most evaluations remain fragmented, often omitting the complex trade offs between ecological benefits, economic feasibility, social acceptance, technological readiness, and institutional support. Recognizing the need for a more holistic lens, this study adopts the Rapid Appraisal for Fisheries (RAPFISH) framework, a flexible multidimensional method originally designed for sustainability assessment in capture fisheries. Through a systematic modification of its attribute structure, we introduce RAPPhytoFeed, a tailored approach for evaluating the sustainability status of phytobiotic feed additive use in poultry farming. RAPPhytoFeed employs Multidimensional Scaling (MDS) to evaluate the sustainability dimensions of phytobiotic practices. This modification enables a context sensitive and stakeholder-informed ordination of sustainability status based on locally relevant indicators. Findings from this study are expected to inform regional feed regulation, support evidence based decision making by producers and stakeholders, and contribute to Indonesia's broader agenda for antibiotic free, climate smart livestock production.

MATERIALS AND METHODS

Ethical Approval

This research did not involve any invasive procedures or animal experiments requiring formal ethical clearance. However, all activities were conducted in accordance with institutional ethical standards for data collection, animal welfare, and respondent consent.

Study Area and Stakeholder Selection

This study was conducted across four major poultry producing districts in South Sulawesi Province, Indonesia: Bone, Pinrang, Gowa, and Sidrap (Figure 1). These districts represent the core production zones for broiler and layer poultry systems in the province, with varying scales of operation and degrees of phytobiotic adoption.

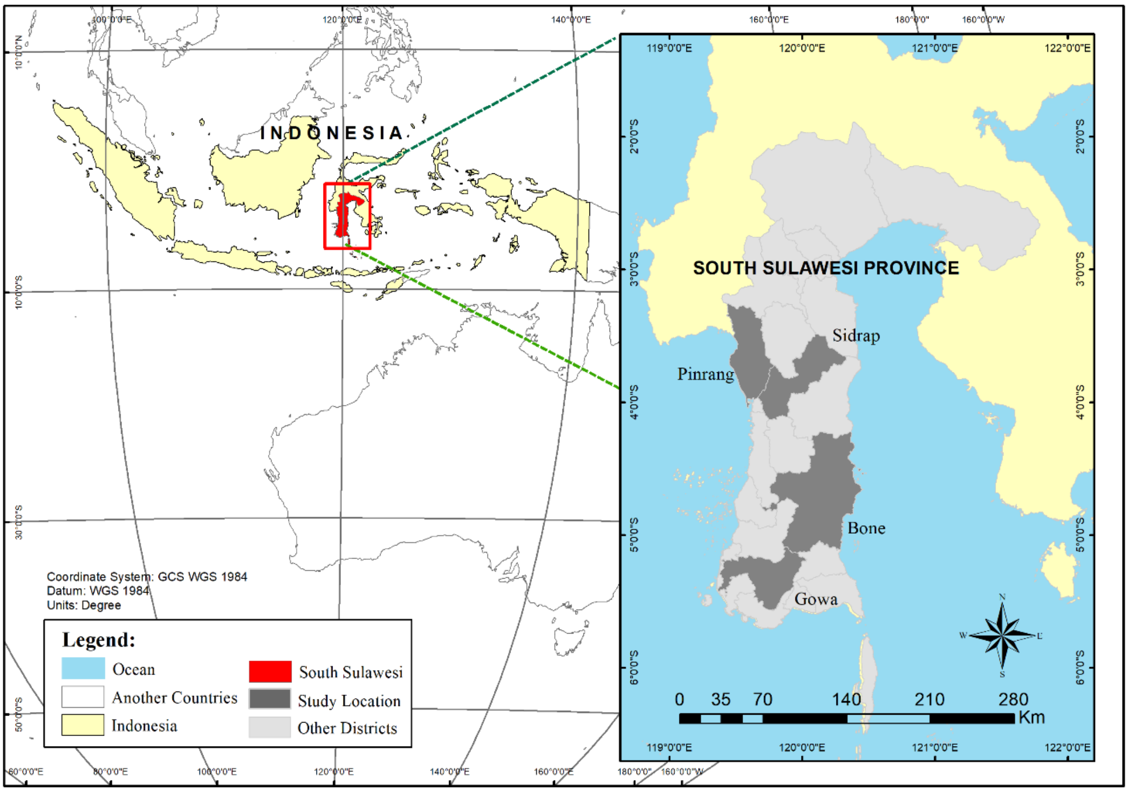


Figure (1): Study area showing the selected districts in South Sulawesi, Indonesia (Source: Geospatial Information Agency of Indonesia. (2024). Administrative Boundaries Map of Indonesia [Map]. Retrieved from https://satupeta.go.id)

Stakeholder perspectives were obtained from five groups with strategic roles in poultry production: (1) Farmers, (2) Extension Workers, (3) Feed Industry Representatives, (4) Government Officers from local agriculture/livestock services, and (5) Academics/Researchers in animal science, veterinary pharmacology, or feed technology. Primary data were collected using purposive sampling through direct observation and structured interviews (Hidayah *et al.,* 2024).

Respondents from groups 1–4 were proportionally selected across four major poultry-producing districts in South Sulawesi (Bone, Pinrang, Gowa, Sidrap), while group 5 was chosen based on scientific expertise in phytogenic feed additives or sustainable poultry systems. Each group comprised 12 respondents: farmers from sub-district farmer groups, five extension agents and five government officers per district, and 12 academic experts from universities, polytechnics, and agricultural colleges in South Sulawesi.

Sustainability Assessment

A modified Rapid Appraisal for Fisheries (RAPFISH) approach was applied to assess the sustainability of phytobiotic feed additive practices in poultry. Originally developed to evaluate fisheries (Kavanagh & Pitcher, 2004; Pitcher & Preikshot, 2001), the method uses Multidimensional Scaling (MDS) to ordinate system performance. In this study, RAPFISH was adapted into RAPPhytoFeed, covering five dimensions (ecological, economic, social, technological, and institutional), each with six tailored attributes. Attribute selection was based on literature and expert input, with ordinal scoring analyzed by MDS to visualize sustainability status (Pitcher *et al*., 2013). The RAPPhytoFeed workflow is shown in Figure 2.

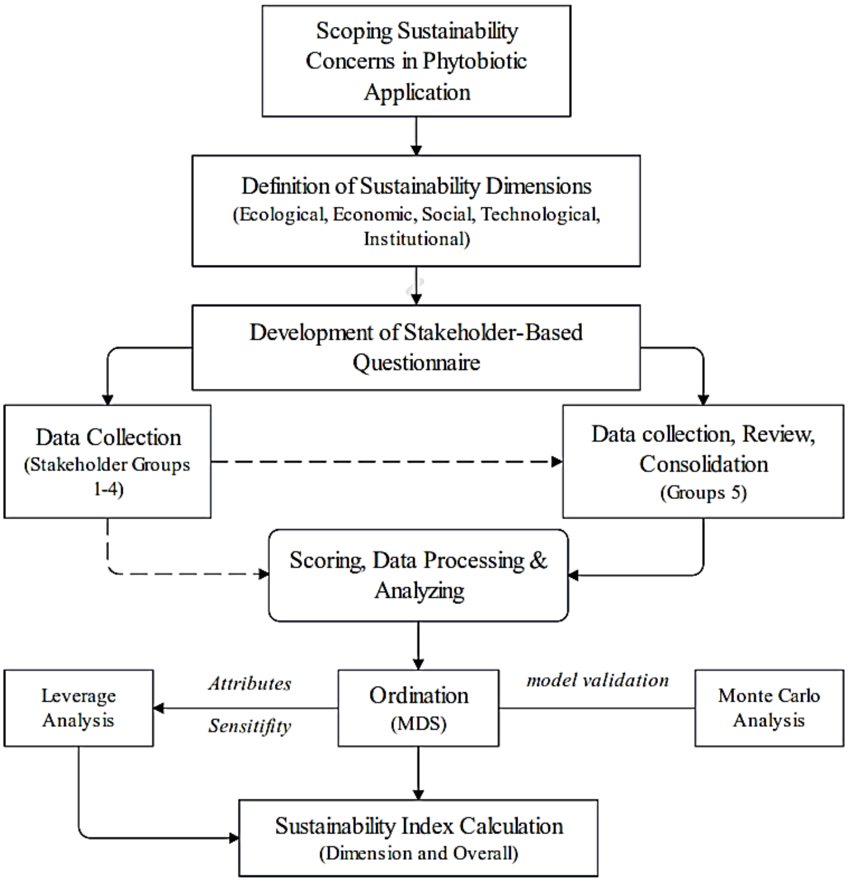


Figure (2) : Analytical workflow of RAPPhytoFeed application for sustainability assessment of phytobiotic feed additives in poultry farming.

Questioner design and evaluation framework

Data were collected through structured questionnaires and ordinal scoring, complemented by qualitative interviews. Sixty respondents participated, with questionnaire items tailored to each stakeholder group but aligned with the same sustainability attributes (Table 1). To ensure consistency, Likert-scale scoring was guided with field explanations, and responses from groups 1–4 were validated and consolidated by experts (Group 5) before final analysis (Figure 2).

Table (1) : Sustainability dimensions, diagnostic attributes, operational definitions, and scoring criteria used to assess the application of phytobiotic feed additives in poultry farming

No	Attributes	Description	Criteria
A	**Ecological Dimension**		
1	FCR Efficiency	The extent to which phytobiotic use can improve feed utilization efficiency (reduce Feed Conversion Ratio) in poultry.	0 = No improvement; 1 = Very slight; 2 = Acceptably improved; 3 = Considerably improved; 4 = Highly efficient FCR
2	Residue & Safety	The level of phytobiotic active compound residues in animal products and their impact on food safety.	0 = Unsafe residue level; 1 = High residue; 2 = Moderate residue; 3 = Low residue; 4 = Residue free / food safe
3	Emissions & Odor	The impact of phytobiotic use on reducing ammonia emissions and odors from poultry manure.	0 = No reduction; 1 = Very slight; 2 = Some reduction; 3 = Strong reduction; 4 = Near zero emissions/odor
4	Biodegradability	The ability of phytobiotic substances to biodegrade without polluting the environment.	0 = Not biodegradable; 1 = Poorly biodegradable; 2 = Somewhat biodegradable; 3 = Mostly biodegradable; 4 = Completely eco friendly
5	Gut Microbiota	The effect of phytobiotics on microbial diversity and balance in the poultry digestive tract.	0 = Harmful disruption; 1 = Minor support; 2 = Partial improvement; 3 = Good balance; 4 = Strongly promotes diverse, healthy microbiota
6	Wastewater Quality	The influence of phytobiotics on the quality of wastewater produced from livestock activities.	0 = Severely contaminated; 1 = Poor quality; 2 = Fair; 3 = Good/acceptable; 4 = Clean / meets discharge standards
B	**Economic Dimension**		
1	Production Cost	The effect of phytobiotic use on the total cost of feed production per unit weight.	0 = Very high cost; 1 = Slightly costly; 2 = Comparable to conventional; 3 = Somewhat more efficient; 4 = Substantially more cost-efficient
2	Farmer Profit	The difference between income and production costs incurred by farmers after using phytobiotics.	0 = Financial loss; 1 = Break even; 2 = Modest net gain; 3 = Clear profit margin; 4 = High profitability/surplus

No	Attributes	Description	Criteria
3	Local Raw Materials	The ease and continuity of phytobiotic raw material supply from local sources.	0 = Not available; 1 = Rare and inconsistent; 2 = Available but limited effort required; 3 = Generally available; 4 = Continuously and readily available
4	Export Potential	The opportunity for AGP-free poultry products to penetrate export markets that prioritize health issues.	0 = No export opportunity; 1 = Very low potential; 2 = Moderate interest; 3 = Strong market potential; 4 = High demand/export ready
5	Investment Capital	The ease of access to capital for small and medium scale enterprises to produce phytobiotics.	0 = No access at all; 1 = Very difficult; 2 = Moderately accessible; 3 = Easily accessible; 4 = Fully supported / incentivized funding environment
6	Economies of Scale	Cost efficiency based on production scale, i.e., whether large scale production is more beneficial or not.	0 = No scale benefits; 1 = Slight savings; 2 = Moderate efficiency; 3 = Good efficiency at scale; 4 = Very high economies of scale
C	**Social Dimension**		
1	Farmer Acceptance	The level of willingness and interest among farmers to adopt phytobiotics in their production systems.	0 = No interest at all; 1 = Limited or hesitant; 2 = Moderate openness; 3 = High willingness; 4 = Widespread and enthusiastic adoption
2	Consumer Perception	Consumers' views on the safety and benefits of poultry products using phytobiotics.	0 = Negative or mistrust; 1 = Indifferent; 2 = Generally positive; 3 = Strong positive belief; 4 = Proactive preference for phytobiotic products
3	Farmer Welfare	Changes in farmers’ economic and social welfare after the use of phytobiotics.	0 = Deteriorated; 1 = No noticeable change; 2 = Slight improvement; 3 = Moderate gains; 4 = Clearly improved welfare and well being
4	Local Product Image	The impact of phytobiotic use on the added value and branding of local poultry products.	0 = Damaged or degraded image; 1 = No effect; 2 = Some improvement in

No	Attributes	Description	Criteria
			image; 3 = Recognizable positive shift; 4 = Strong brand identity and market recognition
5	Farmer Education	The availability and effectiveness of training or extension programs for farmers regarding phytobiotics.	0 = No training available; 1 = Irregular or low quality; 2 = Adequate and routine; 3 = Consistent and useful; 4 = Intensive and highly impactful training/extension
6	Community Support	The level of solidarity and mutual support among farmers in adopting phytobiotic technology.	0 = No peer interaction; 1 = Minimal support; 2 = Occasional encouragement; 3 = Active mutual assistance; 4 = Strong and organized community backing
D	**Technological Dimension**		
1	Production Technology	The availability of adequate tools, systems, or production technology for mixing phytobiotics.	0 = No technology available; 1 = Very limited tools; 2 = Sufficient equipment; 3 = Advanced but partial systems; 4 = Fully equipped and integrated tech
2	Feed Formulation	The simplicity of using phytobiotics in ration formulation by farmers or feed formulators.	0 = Extremely complex; 1 = Hard to use; 2 = Moderately manageable; 3 = User friendly; 4 = Very simple and intuitive
3	Trained Workforce	The availability of skilled or trained personnel in phytobiotic development and application.	0 = No trained personnel; 1 = Few unskilled workers; 2 = Adequate but unevenly distributed; 3 = Skilled staff sufficiently available; 4 = Highly competent and accessible workforce
4	Technological Innovation	The advancement or novelty of technologies applied in phytobiotic product development.	0 = Outdated technology; 1 = Minimal updates; 2 = Some degree of innovation; 3 = Innovative in areas; 4 = State of the art, highly innovative systems

No	Attributes	Description	Criteria
5	Lab Facilities	The availability of laboratory facilities to ensure product quality and effectiveness.	0 = No lab access; 1 = Poor/inadequate labs; 2 = Functional basic lab; 3 = Reliable QA lab; 4 = Full service, certified, high end lab support
6	Technology Adoption	The speed at which farmers are able to adopt and apply new phytobiotic related technologies.	0 = No adoption observed; 1 = Very slow uptake; 2 = Gradual adoption; 3 = Fast integration; 4 = Immediate and widespread adoption
E	**Institutional Dimension**		
1	Policy Support	The existence and effectiveness of government regulations that support phytobiotic use.	0 = No policy at all; 1 = Very weak or symbolic; 2 = Supportive but inconsistent; 3 = Consistently supportive framework; 4 = Robust, comprehensive, and enforced regulation
2	Market Access	The ease with which farmers can market their products to AGP free oriented markets.	0 = Completely inaccessible; 1 = Very limited access; 2 = Some access with constraints; 3 = Generally open and functional access; 4 = Seamless and strategic market integration
3	HR Development	The availability of support such as grants, intellectual property rights, and training from relevant institutions.	0 = No support; 1 = Sporadic and weak; 2 = Occasional structured support; 3 = Routine and targeted HR programs; 4 = Comprehensive and sustainable HR ecosystem
4	Research Institutions	The level of contribution from scientific institutions in research, trials, and development of phytobiotics.	0 = No involvement; 1 = Marginal presence; 2 = Moderate engagement; 3 = Strong contributor; 4 = Leading institution with continuous innovation
5	Distribution & Logistics	The distribution and logistics system that supports phytobiotic dissemination to farmers.	0 = No logistics network; 1 = Fragmented and inefficient; 2 = Functional but limited; 3 = Reliable and responsive supply chain; 4 = Optimized and

No	Attributes	Description	Criteria
			integrated logistics infrastructure
6	Farmer Association Role	The involvement of farmer organizations in promoting, advocating, and supporting phytobiotic use.	0 = Passive or inactive; 1 = Informal participation; 2 = Formal but modest role; 3 = Active involvement; 4 = Strong leadership and organized advocacy

Ordination and Validation (MDS and Monte Carlo)

The sustainability index for each dimension and the overall system was derived using Multidimensional Scaling (MDS) in a modified RAPFISH framework. This approach transforms ordinal stakeholder scores into spatial configurations, positioning sustainability profiles across five dimensions (ecological, economic, social, technological, institutional). The resulting index (0–100) was interpreted using established classification schemes (Frimawaty *et al*., 2013; Hidayah *et al*., 2024; Rachman *et al.,* 2022) as shown in Table 2.

Table (2) : Classification of Sustainability Index

No	Index Interval	Status
1	0–25	Unsustainable
2	25.01–50	Less Sustainable
3	50.01–75	Moderately Sustainable
4	75.01–100	Sustainable

A Monte Carlo simulation with 25 iterations was used to validate the robustness of the MDS ordination by introducing controlled perturbations to detect sensitivity and bias. Model stability was confirmed when differences between original and simulated outputs were <5%, with diagnostic thresholds of stress <0.25 and R^2 >0.90 (Frimawaty *et al*., 2013; Lloyd Chrispin *et al*., 2022; Pitcher *et al.,* 2013; Tamrin et al., 2025). As the original Excel-based RAPFISH module using g77ALSCAL.dll and macros is no longer functional (Alder *et al*., 2000), all analyses were replicated in R-Studio, applying ALSCAL multidimensional scaling, score normalization, and axis rotation as established by Kavanagh and Pitcher (2004) to ensure transparency, reproducibility, and consistency.

Sensitivity Analysis (Leverage)

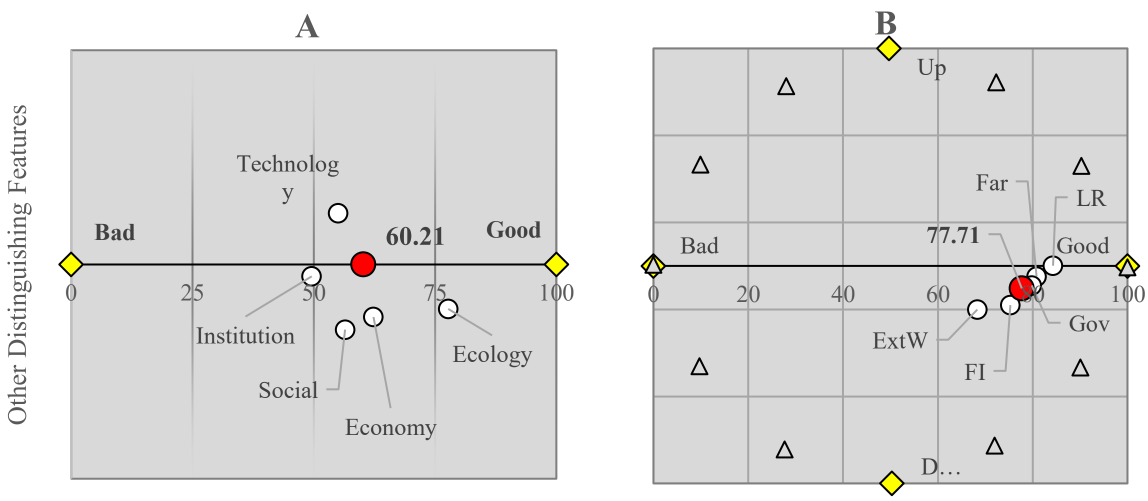
Leverage analysis was applied using the Root Mean Square (RMS) change method from the RAPFISH framework (Kavanagh and Pitcher, 2004; Pitcher & Preikshot, 2001). This technique evaluates the sensitivity of MDS results by perturbing attribute scores (0–3) while holding others constant (Hidayah *et al.,* 2024; Jimenez *et al*., 2021).

Higher RMS values indicate attributes with stronger influence, serving as leverage points for sustainability improvement (Alder *et al*., 2000). In this study, leverage scores were computed in R-Studio following the original RAPFISH logic (Kavanagh and Pitcher, 2004), and attributes exceeding the mean leverage were identified as priorities for policy or management action.

To complement this, Euclidean distance (ΔEuclid) was calculated between stakeholder groups using sustainability index scores from MDS. Distances ≥1.0 indicated substantial divergence in perception, while values <1.0 reflected consensus (Pitcher and Preikshot, 2001), highlighting potential gaps in stakeholder alignment and communication.

RESULTS

The sustainability status of phytobiotic feed additive practices in South Sulawesi was evaluated across five key dimensions: ecological, economic, social, technological, and institutional. The overall sustainability status of the system is considered as "Moderately Sustainable" (Figure 3A), however ordination results based on Multidimensional Scaling (MDS) revealed marked variation in sustainability performance across these dimensions, suggesting that stakeholder perspectives recognize differing levels of maturity, readiness, and systemic support for phytobiotic integration. The ecological and economic dimensions exhibit stronger sustainability performance (Figure 3B & 3C), reflecting perceived benefits such as improved feed efficiency, reduced emissions, and the feasibility of cost-effective phytobiotic use in feed production. Conversely, the institutional dimension appears weakest (Figure 3F), indicating structural limitations such as insufficient policy backing, inadequate market facilitation for AGP free products, and weak organizational support systems. The social and technological dimensions occupy intermediate positions (Figure 3D), suggesting that while adoption is occurring, it remains constrained by factors such as farmer knowledge, innovation diffusion, and logistical access.



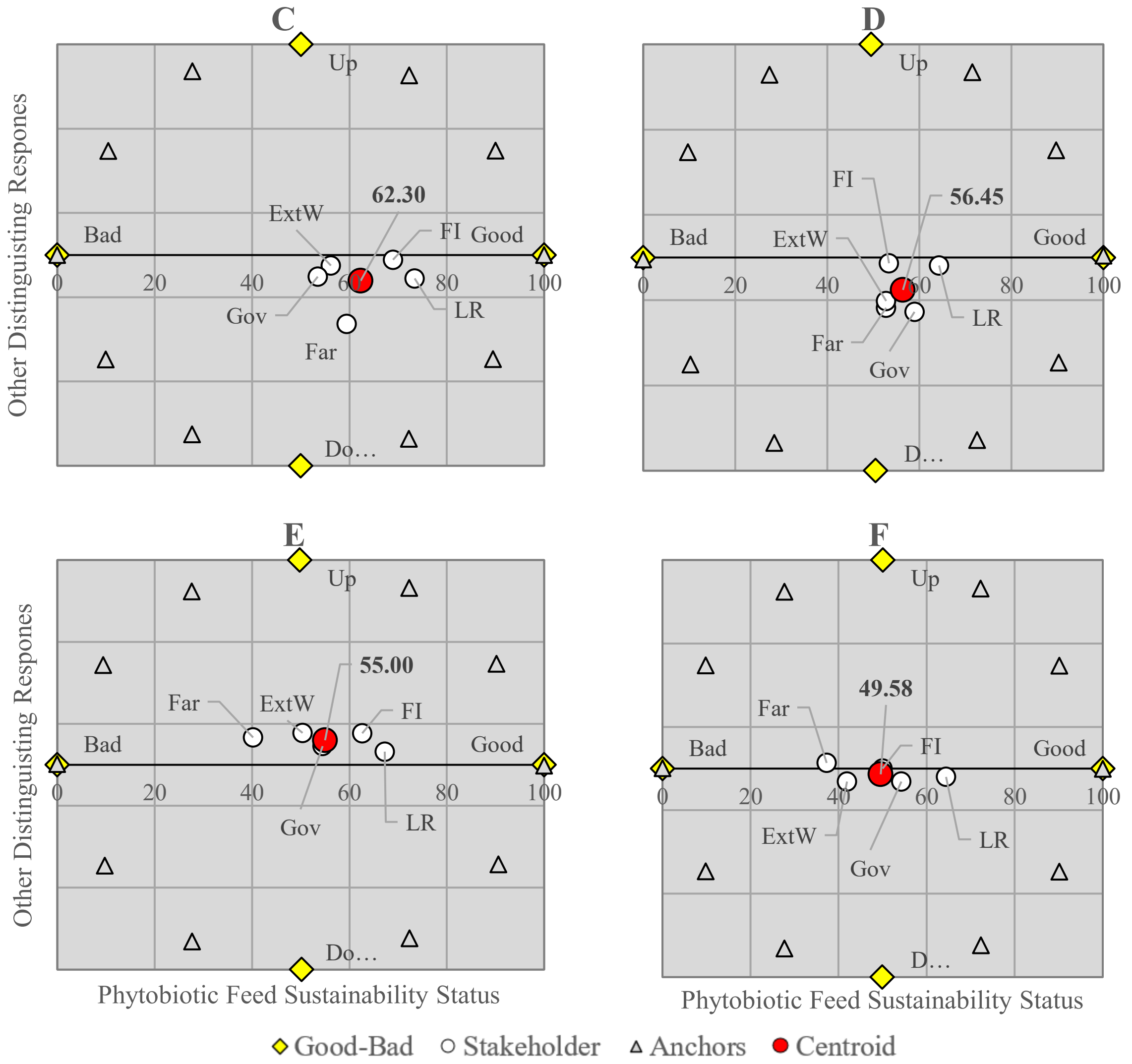


Figure (3) : Ordination plot showing the sustainability status of phytobiotic feed additive practices across five dimensions: A: Overall Status, B: Ecology, C: Economy, D: Social, E: Technology, and F: Institution. Far: Marmers, ExtW: Extension Workers; FI: Feed Industries; Gov: Government

To assess the stability and reliability of the ordination outcomes, a Monte Carlo simulation was performed using 25 iterations. The simulation introduced controlled perturbations to the original attribute scores, enabling the evaluation of model sensitivity to potential scoring bias. As presented in Table 3, the resulting differences between the MDS and Monte Carlo outputs were consistently minimal across all dimensions, indicating a high degree of internal consistency in the stakeholder based scoring process. Additionally, the ordination results produced low stress values (all below 0.075) and high coefficients of determination ($R^2 > 0.96$), both of which are recognized benchmarks for the robustness of MDS configurations. These statistical diagnostics reinforce the reliability of the model and affirm that the sustainability indices generated in this study are valid representations of stakeholder perceptions. The consistency of the results also provides a solid foundation for identifying key leverage points and formulating responsive sustainability strategies in subsequent analyses.

Table (3) : Results of MDS ordination, Monte Carlo validation, and statistical diagnostics for each sustainability dimension

Dimensions	Sustainability Ordination		Differences [ABS]	S-Stress	R^2	Iteration
	MDS	Monte Carlo				
Ecology	77.71	78.216	0.508	0.068	0.974	25
Economy	62.30	62.214	0.089	0.071	0.969	25
Social	56.45	55.916	0.532	0.074	0.967	25
Technology	55.00	54.647	0.349	0.072	0.968	25
Institution	49.58	49.618	0.042	0.073	0.966	25

These findings highlight the uneven development of sustainability components and underscore the need for targeted interventions, particularly in governance and institutional capacity, to complement the already promising ecological and economic aspects of phytobiotic use in poultry systems.

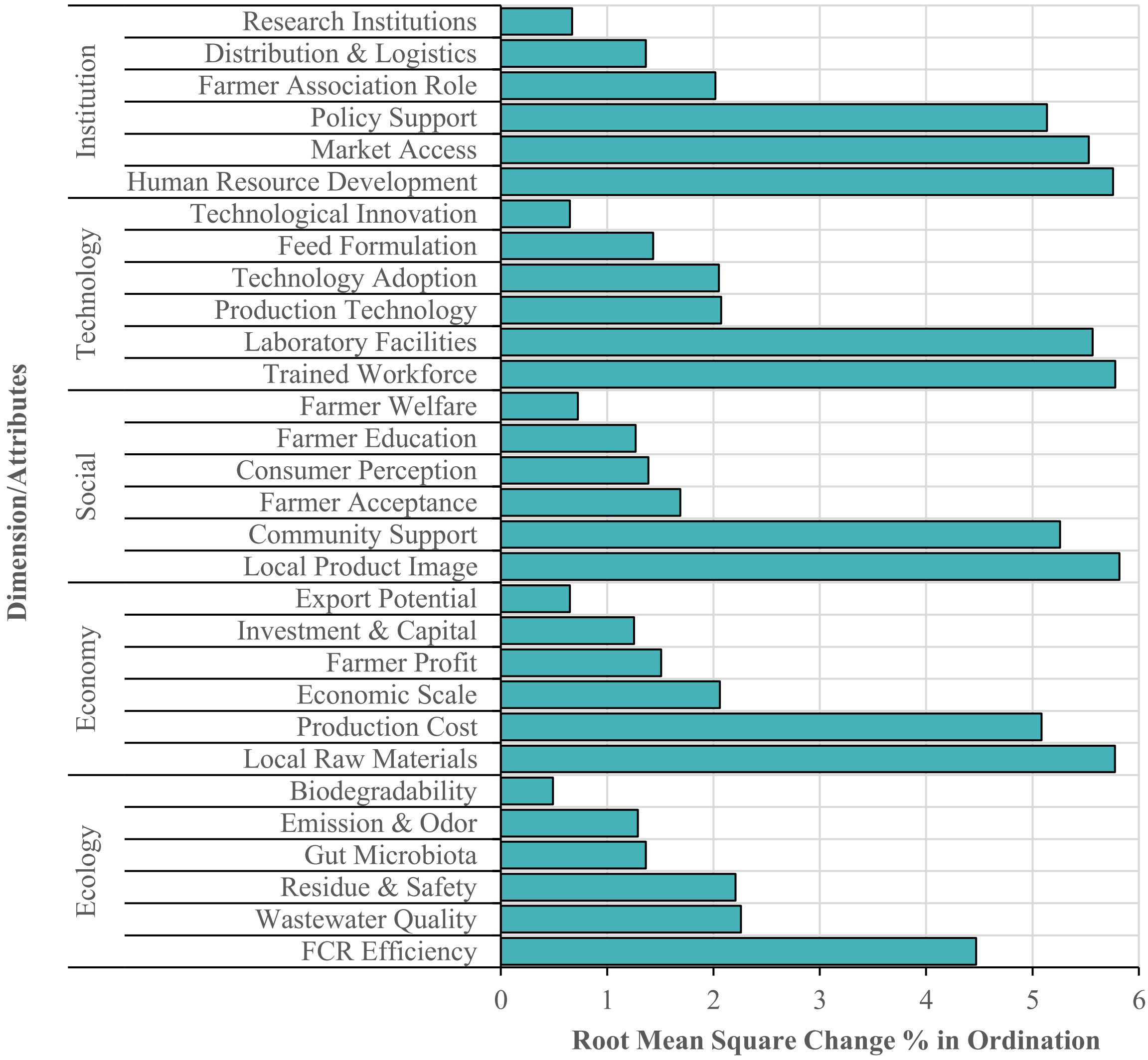


Figure (4) : Leverage analysis of sustainability attributes based on Root Mean Square (RMS) change % in ordination score upon attribute removal.

Leverage analysis was conducted to identify the most influential attributes within each sustainability dimension, attributes with higher RMS values are considered to have greater leverage, indicating a stronger influence on the overall sustainability index. Within the ecological dimension, FCR efficiency, wastewater quality, and residue & safety emerged as the most critical attributes, underscoring the importance of phytobiotic effectiveness and environmental safety in shaping stakeholder evaluations. In the economic dimension, local raw materials and production cost showed the highest leverage, reflecting concerns about feed input availability and cost efficiency. For the social dimension, community support and farmer acceptance had the greatest impact, suggesting that social capital and willingness to adopt play key roles in sustainability. In the technological dimension, trained workforce and laboratory facilities were the dominant attributes, highlighting the technical readiness and institutional infrastructure needed to support phytobiotic integration. Meanwhile, in the institutional dimension, human resource development, market access, and policy support were the top leverage points, indicating that sustainability advancement is tightly linked to systemic support and regulatory facilitation (Figure 4).

Table (4) : Euclidean distance (ΔEuclid) between stakeholder groups across five sustainability dimensions

Dimensions	Extension workers	Farmers	Feed Industry	Govern-ment	Lecturer & Researcher
	--*ΔEuclid*--				
Ecology	1.7304★	0.8960	1.7520★	1.1495★	0.5663
Economy	0.0410	1.1239★	0.0297	0.2821	0.4152
Social	0.0411	0.0445	0.0579	0.2484	0.4475
Technology	0.1054	0.2297	0.2566	0.0706	0.3512
Institution	0.1386	0.1057	0.0034	0.1295	0.1270

★indicates *divergent perception* among stakeholder groups (*ΔEuclid* ≥ 1.0); values without the symbol indicate relatively *consensual perceptions*.

Inter stakeholder Euclidean distances (*ΔEuclid*) were calculated to assess the degree of perceptual variation across the five sustainability dimensions. As shown in Table 4, these variations were not uniformly distributed. Although the ecological dimension recorded the highest sustainability index, it also exhibited the greatest divergence in stakeholder perception, with particularly high *ΔEuclid* values observed between extension agents and feed industry representatives. This indicates that while the ecological benefits of phytobiotics are broadly recognized, their perceived relevance differ among actors with distinct roles, interests, and levels of engagement in the field. In contrast, the institutional and technological dimensions showed lower inter group distances, indicating a relatively higher degree of consensus among stakeholders. This could reflect shared concerns about systemic support, infrastructure, and policy clarity in the context of phytobiotic adoption.

DISCUSSION

Sustainability performance across dimensions

Ecology

The sustainability appraisal highlights how stakeholder perceptions vary in terms of readiness and systemic support across the five dimensions. Dimensions related to environmental performance and economic feasibility are perceived more favourably, suggesting that the practical benefits of phytobiotics, such as improved production efficiency and reduced environmental impact, are well acknowledged by those directly involved in the field. This aligns with existing studies on phytogenic additives, which emphasize their role in improving gut health, lowering ammonia emissions, and contributing to feed conversion efficiency (Abd El-Hack *et al*., 2022; Aminullah *et al*., 2025; Kuralkar and Kuralkar, 2021; Rafiq *et al*., 2022).

Within the ecological dimension, feed conversion ratio (FCR) efficiency and wastewater quality emerged as key leverage factors (Figure 4). Improved FCR enhances feed efficiency, reduces excreta volume, and lowers organic load in wastewater, thereby mitigating environmental waste. Poor manure management can cause odor, vector attraction, groundwater contamination, and phytotoxicity (Hamidu *et al.,* 2024; Kolawole *et al*., 2025). Phytobiotics such as *Punica granatum* have been shown to reduce fecal ammonia and methanethiol while improving gut health (Ahmed and Yang, 2017; Obianwuna *et al*., 2024). Similarly, supplementation with Bacillus amyloliquefaciens suppresses ammonia and hydrogen sulfide emissions, offering ecological benefits alongside performance gains (Ahmed *et al*., 2014).

Phytobiotics offer both ecological and economic benefits by improving growth, gut health, and pathogen control while reducing reliance on synthetic antimicrobials and environmental risks (Alagawany *et al.,* 2021). Macleaya cordata extract enhances gut integrity and suppresses necrotic enteritis (Song *et al.,* 2023), while oregano combined with Bacillus subtilis improves immune response and nutrient absorption (El-Sayed *et al.,* 2024). Supplementation with essential oils, saponins, and tannins has shown strong anticoccidial effects against Eimeria spp., surpassing salinomycin in reducing oocyst shedding and lesion severity (Galamatis *et al.,* 2025). Likewise, turmeric and garlic extracts, especially in combination (2.5% TE + 2% GE), significantly increased duodenal villus morphology, with the greatest villus height and surface area recorded in the combined treatment (Purwanti *et al.,* 2014).

Economy

The economic dimension highlighted the critical role of production costs and market value, underscoring the need for competitive pricing and economic benefits to drive the adoption of sustainable alternatives in poultry farming (Coyne *et al.,* 2020). In the economic domain, local raw material availability and production cost emerged as central concerns (Figure 4), suggesting that affordability and sourcing flexibility remain key levers for sustaining phytobiotic use in poultry systems. The sustainability potential of phytobiotic use is closely linked to the local availability of botanical resources. In countries like Indonesia, which are rich in nutraceutical plant diversity, this offers a distinct advantage (Cahyaningsih *et al*., 2021; Ikrar Musyaffa *et al.*, 2024).

The widespread presence of locally available and low cost medicinal plants encourages farmers to adopt natural phytogenic feed additives rather than relying on commercial products. For example, phytobiotics such as *Andrographis paniculata* and *Origanum vulgare* have been reported to significantly improve feed efficiency and carcass quality (Jahja *et al*., 2023), while reducing dependence on expensive pharmaceutical inputs. In addition, a lower incidence of gut related diseases and enhanced nutrient digestibility further contribute to improved feed conversion ratios and reduced production losses (Abdul Basit *et al.,* 2020; Hashem *et al*., 2022).

Medicinal plants serve as a valuable source of phytogenic feed additives due to their rich composition of bioactive secondary metabolites. These compounds exhibit broad spectrum biological functions including antimicrobial, antioxidant, immunomodulatory, and growth promoting effects, making them effective and natural alternatives to synthetic antibiotics (Alagawany *et al*., 2021; Ivanova *et al.,* 2024; Ren *et al.*, 2025). The incorporation of phytobiotics into animal diets has been shown to reduce morbidity and mortality, improve animal welfare, and lower the risk of antibiotic residues entering the human food chain (Ahmed and Yang, 2017; Seong Wei *et al.*, 2024). As such, phytobiotics offer a sustainable, health oriented, and economically viable approach to improving livestock production while aligning with global demands for safer and more responsible food systems (Aminullah et al., 2025).

Social

In the social dimension, the attributes local product image and community support were identified as the most influential leverage points (Figure 4). This finding suggests that sustainability in phytobiotic adoption is not solely a matter of individual decision making but is also deeply embedded in collective values and social dynamics within the poultry sector. The high leverage of local product image underscores the importance of consumer perception and identity attached to regional products, particularly in areas where traditional farming communities value food origin and natural inputs. (Ivanova *et al.*, 2024) noted that phytogenic additives improve product acceptability and trust among health conscious consumers. The enhancement of product reputation through phytobiotic use could thus offer a socially resonant pathway for encouraging adoption.

Meanwhile, the prominence of community support indicates that peer networks, farmer associations, and informal knowledge sharing remain central to technology dissemination in rural and peri urban production systems. This aligns with previous research emphasizing that social cohesion and farmer to farmer trust are key determinants in the uptake of antibiotic alternatives and sustainable practices (Bennett *et al*., 2019). However, stakeholder perception data revealed noticeable inter group divergence, particularly between extension agents and feed industry representatives. These differences likely reflect varying proximity to end users and asymmetries in how value and risk are perceived along the production chain. While community level actors may prioritize social acceptance and reputational outcomes, commercial actors may focus more on technical feasibility and market scalability. This divergence highlights the need for targeted engagement strategies, including participatory education, peer led demonstration trials, and consumer communication efforts (Bist *et al.*, 2024) in fostering multi actor alignment for sustainable poultry transitions.

Technology

Technological factors such as trained personnel and adequate laboratory facilities are crucial for consistent application and quality control of phytogenic feed additives. These plant derived compounds (herbs, spices, fruits) show variable efficacy, influenced by composition, dosage, and bird physiology (Abdelli *et al.,* 2021; Diaz-Sanchez *et al.,* 2015; Obianwuna *et al.,* 2024; Krauze, 2021). Optimizing their use requires precise formulation, proper delivery systems (e.g., nanoencapsulation, AI-based precision nutrition), and stringent quality assurance. When well integrated, phytobiotics can improve gut health, antioxidant status, and nutrient absorption, though benefits depend on formulation and production practices (Goh *et al.,* 2025; Gumowski *et al.,* 2025; Perera and Ravindran, 2025).

Limited technical capacity, particularly in terms of trained personnel for phytobiotic formulation and inadequate laboratory infrastructure, presents a significant barrier to consistent product quality and reliable field outcomes (Moore, 2024). Botanical based additives containing essential oils, flavonoids, or saponins are chemically sensitive to environmental conditions such as temperature, moisture, and oxidation. As a result, they require standardized processing methods and stability testing to maintain their bioactive potency (Ivanova *et al.,* 2024; Movahedi *et al.,* 2024). Without laboratory validation protocols and adequately trained technicians, these products are at risk of delivering inconsistent results in livestock performance and health enhancement.

This gap in technical infrastructure and human capacity becomes especially critical in small and medium scale production systems, where access to laboratory services, standardized formulations, and technical supervision is often limited (Mehr *et al*., 2024; Silpi, 2025). Unlike large commercial operations with integrated R&D capabilities, these producers may rely on unverified formulations or anecdotal guidance, increasing the risk of inconsistent application (Kumraj *et al*., 2022; Surya *et al.,* 2021). In such contexts, the absence of formalized training and lack of quality benchmarks can result in suboptimal outcomes that diminish user confidence in phytobiotic products (Perera and Ravindran, 2025). To support equitable adoption across production scales, there is a growing need for decentralized quality assurance mechanisms, including mobile diagnostics, regional formulation hubs, and partnerships with agricultural institutions (Bist *et al.*, 2024; Krauze, 2021). Such initiatives would help reduce the technological divide while promoting more consistent, evidence based use of phytobiotics as part of sustainable feed strategies.

Institution

The institutional dimension was most influenced by the state of human resource development and market access, underscoring the systemic nature of phytobiotic sustainability and the reliance on external structures to support integration at scale (Figure 4). Dimensions linked to institutional support appear to face greater inertia. These aspects, while not necessarily contested, often suffer from lagging coordination between policy frameworks, knowledge systems, and practical implementation. Previous research has similarly pointed to weak regulatory guidance and uneven extension services as common constraints in integrating alternatives to antibiotic growth promoters (Abdelli *et al.,* 2021; Grashorn, 2010). This reflects broader challenges in many low and middle income food systems, where antibiotics function not merely as medical inputs but as infrastructural supports sustaining small and medium scale producers under competitive and weakly regulated value chains (Bennett *et al*., 2019; Hughes *et al.*, 2024).

Attributes such as Human Resource Development and Market Access, which showed high leverage values, underscore the importance of integrated policies and institutional investments to accelerate phytobiotic adoption. Small and medium scale agricultural enterprises often face significant barriers in adopting sustainable technologies without structured financial incentives and advisory support (Castillo-Díaz *et al.*, 2025). Similarly, the value of institutional frameworks that promote data based livestock management, which can be extended to phytobiotic practices requiring consistent monitoring, formulation control, and performance validation (Tullo *et al.*, 2019). Addressing these institutional gaps is therefore critical not only for improving stakeholder confidence but also for mainstreaming sustainable, antibiotic free poultry systems.

The shift to phytobiotic-based practices remains uneven, especially in hybrid production systems spanning informal and formal markets. While effective under controlled conditions, their consistency in commercial farming is limited by management variability, lack of standardized protocols, and inadequate infrastructure and expertise (Moore, 2024). The low institutional sustainability index reflects broader global challenges in aligning regulation, training, and distribution for antibiotic-free production (Gargate *et al.,* 2025; Sivapirunthep *et al.,* 2025). These systemic constraints not only slow adoption but also weaken farmer confidence, highlighting the need for integrated strategies that combine product development with capacity building, farmer engagement, and policy support.

Implications for Sustainability Integration and Policy Focus

The integration of phytobiotic feed additives into poultry farming systems offers a compelling pathway toward sustainable animal production, particularly through gains in ecological and economic performance. The strong leverage of attributes such as feed conversion ratio (FCR) efficiency, wastewater quality, and local raw material availability indicates that phytobiotics can reduce environmental burdens and enhance cost efficiency. However, the overall sustainability of these practices is constrained by weaker performance in the social, technological, and institutional dimensions. Low scores in areas such as trained workforce, laboratory infrastructure, policy support, and market access highlight systemic bottlenecks that may hinder adoption, especially among small and medium scale producers. These findings underscore the importance of moving beyond input substitution strategies and toward a more integrated sustainability framework that addresses enabling conditions across all dimensions.

For phytobiotics to achieve their full potential as a sustainable alternative to antibiotic growth promoters (AGPs), they must be supported by coherent strategies that reinforce technical capacity, social engagement, and institutional readiness. This includes expanding farmer training on phytobiotic formulation and use, investing in laboratory testing capacity to ensure product quality and safety, and fostering peer to peer learning platforms to strengthen community level acceptance. As highlighted by Tullo *et al*. (2019), technological interventions such as precision livestock systems can improve resource efficiency but require institutional facilitation. Similarly, Castillo-Díaz *et al.* (2025) emphasize that the adoption of sustainable innovations is often limited by financial and policy constraints, which can be addressed through targeted subsidies, green credit lines, and public private partnerships.

To support policy coherence and cross sectoral implementation, national livestock development strategies should consider incorporating phytobiotics within broader agendas of antimicrobial resistance (AMR) mitigation, environmental protection, and rural economic empowerment. Practical steps may include the development of phytobiotic standards within veterinary and feed regulations, financial incentives for local phytobiotic producers, and integration into animal health extension services. Moreover, collaboration among universities, industry actors, and regulatory bodies will be critical for generating context specific evidence and translating research into action. A coordinated approach that aligns ecological promise with institutional commitment can help position phytobiotics as a keystone element in the transformation toward resilient and sustainable poultry production systems.

CONCLUSIONS

This study provides the first comprehensive, stakeholder-informed assessment of the sustainability of phytobiotic feed additive practices in South Sulawesi's poultry sector. By adapting the RAPFISH framework into a customized RAPPhytoFeed approach, the ecological, economic, social, technological, and institutional dimensions of phytobiotic adoption were evaluated within real world production settings.

The ecological and economic dimensions of phytobiotics demonstrate strong sustainability through feed efficiency, local raw material use, and cost benefits, yet overall progress remains constrained by institutional, technological, and social factors. Key leverage factors such as trained workforce, laboratory capacity, human resource development, and market access highlight the need for supportive systems. Transitioning from antibiotic-based practices requires not only effective alternatives but also integration with capacity building, infrastructure, and policy alignment, while differences in stakeholder perceptions emphasize the importance of inclusive planning and communication.

Phytobiotics hold strong potential as a sustainable feed strategy in Indonesia's poultry industry, but realizing this requires multisectoral coordination, targeted investment, and adaptive regulatory support. Further research should validate long term outcomes under commercial conditions and expand participatory frameworks for large scale sustainability monitoring.

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CONFLICT OF INTEREST

The authors state that there are no conflicts of interest with the publication of this work.

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