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The Potential of Plant By-Products as the Agents to Reduce Emissions: Study Case on Farmer's Perspectives in South Sulawesi, Indonesia

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ABSTRACT

In Indonesia, agriculture, particularly livestock farming, plays a significant role in the economy and environmental impact. This study explores the perspectives of farmers in South Sulawesi regarding the potential of plant by-products as agents to reduce emissions, focusing on their utilization in livestock feed. By conducting interviews and surveys among farmers, this research investigates current practices, challenges, and perceptions towards integrating plant by-products into feed formulations. The findings highlight the feasibility and barriers perceived by farmers in adopting these sustainable practices, considering economic viability, nutritional benefits, and environmental sustainability. There were low levels of awareness and understanding among farmers in the two selected districts in Bone Regency (Tanete Riattang and Tanete Riattang Timur) regarding the utilization of plant by-products as natural feed additives (Phyto-biotic) and their potential role in mitigating greenhouse gas emissions (only 10% aware). While the concept of using Phyto-biotics for environmental benefits was relatively unfamiliar to most respondents, there was a significant awareness of using ginger, as individual substrate to enhance palatability and livestock appetite when the cattle experienced health problem. Insights from this study contribute to understanding local perspectives on mitigating livestock emissions through innovative feed strategies, informing policy and practical interventions aimed at promoting sustainable agriculture in Indonesia.

1. INTRODUCTION

South Sulawesi Province holds a geographically strategic position that makes it an essential region for economic, cultural, and logistical activities within Indonesia and Southeast Asia. Its central location in the Indonesian archipelago places it at the intersection of major maritime and terrestrial trade routes, linking the western and eastern parts of the country [1]. This strategic advantage enhances its role as a transit hub for goods, services, and people, contributing significantly to national development.

The utilization of horticultural plant by-products as Phyto-biotic agents to mitigate greenhouse gas emissions presents a novel and sustainable approach to addressing environmental challenges in South Sulawesi's livestock sector. As a region with a rich agricultural base, South Sulawesi produces significant quantities of horticultural crops, such as sweet potatoes, cassava, bananas, and moringa. These crops generate by-products, including leaves, stems, and peels, that are often discarded or underutilized [2, 3]. These by-products are rich in bioactive compounds with potential applications as natural feed additives, particularly in reducing enteric methane emissions from ruminants.

This study was located in the regency of Bone, province of South Sulawesi. Bone Regency, also known as 'Bumi Arung Palakka,' is one of the regencies in South Sulawesi Province, which serves as a center for the development of beef cattle. It spans a total area of 4,559.0 km^2 with a population of 801,775 individuals, yielding an average population density of 162 people/km^2. Bone Regency comprises 27 districts and is strategically located, further enhanced by the presence of Bajoe Port connecting it to other provinces, thereby making Bone Regency significant in trade, services, and livestock in the Eastern Indonesia region [4]. The distance from Bone Regency to Makassar, the provincial capital of South Sulawesi, is approximately 3 hours. Based on statistical data from Bone Regency, beef cattle are the most populous ruminant livestock, with a population of 436,363 heads in 2022, slightly lower by 0.04% compared to the previous year, 2021, which recorded 452,347 heads. Despite this slight decline, Bone Regency retains the distinction of having the largest population of beef cattle among regencies in South Sulawesi. However, it becomes a concern, as increasing the population of cattle has been the target of the ministry of agriculture and the increase amount of emissions from cattle is in line with the increase in the number of cattle [5]. It is necessary to find a proper solution for the sustainability of cattle farm.

Bone Regency is rich in bio-pharmaceutical plants, which can be utilized as feed additives for beef cattle to enhance their appetite and strengthen their immune system, particularly during transitional seasons. The application of bio-pharmaceutical plants in ruminant livestock management serves as a strategy to reduce antibiotic usage, as improved immune resilience is expected to protect livestock from pathogenic microorganisms, especially when combined with continuous sanitation practices in the farming environment. The use of bio-pharmaceutical plants as Phyto-biotics in beef cattle production not only benefits the livestock but also contributes to environmental sustainability.

Incorporating horticultural by-products as Phyto-biotics offers multiple benefits. Economically, it provides a value-added use for agricultural waste, reducing the reliance on expensive commercial feed additives. This can lower feed costs and increase the profitability of livestock farming. Environmentally, the practice contributes to mitigating the environmental footprint of ruminant livestock, which is a significant source of methane emissions—a potent greenhouse gas [6]. By repurposing agricultural residues, this approach also aligns with principles of circular economy and sustainable resource management, making it a model for climate-smart agriculture in Indonesia.

The use of herbal remedies in beef cattle farming systems has gained increasing attention as an alternative approach to enhancing livestock health and productivity. Herbal remedies, which consist of various bio-pharmaceutical plants such as turmeric (Curcuma longa), ginger (Zingiber officinale), Javanese ginger (Curcuma xanthorrhiza), and betel leaf (Piper betle), contain bioactive compounds that function as immunostimulants, antioxidants, and natural antimicrobial agents [7, 8].

Farmers' understanding of formulating herbal remedies is a crucial aspect in supporting the sustainable health and productivity of beef cattle. With proper utilization, herbal remedies can serve as a natural solution to improving livestock immunity, optimizing digestion, and reducing dependence on antibiotics.

This study aimed to: 1). assess the level of awareness and understanding among farmers in two districts in Bone Regency, South Sulawesi regarding the utilization of plant by-products as natural feed additives (Phyto-biotics) and their potential role in mitigating greenhouse gas emissions, as Bone Regency is the main beef cattle supplier for eastern Indonesia; and 2). investigate farmers' perspectives on the potential benefits, challenges, and feasibility of incorporating plant by-products into livestock feeding practices. In the future, this study will be useful for recommendations for integrating plant by-products into livestock feeding strategies, tailored to the socio-economic and ecological context of South Sulawesi, to promote sustainable and low-emission agriculture.

2. MATERIALS AND METHODS

2.1 Locations of the study

The research was conducted in South Sulawesi Province, Indonesia, with a specific focus on Bone Regency, recognized for its significant agricultural and livestock activities. South Sulawesi encompasses a diverse range of agro-ecological zones, including coastal lowlands, fertile plains, and mountainous regions, which support the cultivation of various horticultural crops such as sweet potatoes, cassava, bananas, and moringa. The strategic selection of Bone Regency was due to its prominence in livestock farming and its accessibility to various horticultural by-products, making it an ideal case study for investigating farmers' perspectives on phytobiotic utilization. The districts focused on the study were: District of Tanete Riattang and District of Tanete Riattang Timur. The selection of Tanete Riattang and Tanete Riattang Timur districts in Bone Regency as research areas for the use of herbs in beef cattle feed can be attributed to several critical factors that align with the objectives of the study. Tanete Riattang and Tanete Riattang Timur have abundant natural resources, including a wide range of herbal plants that can be utilized as feed ingredients. The region's rich biodiversity offers significant opportunities for exploring local plants that possess potential benefits in livestock nutrition. The presence of diverse plant species that are indigenous to the area could provide a valuable resource for testing the efficacy of herbal additives in cattle feed, contributing to both environmental sustainability and the health of the livestock.

The local knowledge and traditional practices in the Tanete Riattang and Tanete Riattang Timur communities might play a crucial role in the research. In rural areas, there is often a wealth of traditional ecological knowledge, particularly regarding the use of plants for medicinal or nutritional purposes. These communities may already have informal practices involving herbal plants in animal husbandry, creating a solid foundation for introducing more systematic research into the role of herbs in livestock diets. Such local knowledge not only facilitates the acceptance of new practices but also ensures the research is grounded in the community's experience and cultural context with approximately about 80% of the local people in these districs involve in cattle farming making it an ideal location for conducting research on sustainable livestock practices. Communities with an active engagement in agricultural and livestock production tend to be more receptive to innovations that promise to improve productivity and environmental outcomes. The involvement of farmers in the research process can also lead to more effective dissemination of findings, ultimately accelerating the adoption of herbal feed practices.

Moreover, the geographic and socio-economic context of Tanete Riattang and Tanete Riattang Timur aligns well with the broader goals of the research. With increasing concerns over the environmental impact of conventional livestock farming, particularly in terms of methane emissions, these districts present an ideal setting to explore alternative, sustainable practices.

The introduction of herbal feed additives, known for their potential to reduce methane production in ruminants, could provide significant benefits in mitigating the environmental footprint of beef cattle farming in the region.

This research could serve as a model for promoting sustainable livestock practices in other parts of Indonesia, supporting both environmental and economic sustainability.

2.2 Participants

Participants in this study consist of parties deemed capable of adequately providing insights into the issues under investigation. Therefore, the researcher needs to outline the criteria for potential participants as an initial guide for commencing data collection. Potential participants are selected using a theoretical sampling approach, where sampling is based on concepts proven to be theoretically related to the theory being developed. The identified participants in this research are:

a. Subdistrict Head (Camat), who assists in providing information on more sustainable livestock systems that can reduce environmental impact and improve the welfare of farmers and the community in their area.

b. Village Secretary, who provides information on environmentally friendly and sustainable livestock systems at the village level, thus positively impacting the welfare of farmers and reducing negative environmental impacts.

c. Field Extension Officer, who is the main driver in the implementation of sustainable livestock farming based on Phyto-biotics, which benefits farmers economically and has positive environmental impacts.

d. Head of Livestock Farmer Group, who is a key driver in adopting sustainable livestock farming technologies, thereby improving the welfare of farmers and helping to reduce environmental impacts from the livestock sector.

2.3 Study design

This study employs a qualitative approach using the Grounded Theory method. A qualitative approach can be understood as a process-oriented approach that allows for the discovery of various data and facts. The focus of the research is on the perspectives of participants from diverse backgrounds in understanding and interpreting their experiences regarding the use of plant by-products as phytobiotic agents for emission reduction.

The study utilizes the Grounded Theory method because it is expected to generate new concepts, approaches, or theories derived from findings obtained during the research process. The goal of Grounded Theory is data theorization, a method of theory development that is action- and interaction-oriented within the research field. This approach is highly suitable for the subject under investigation, as the researcher seeks to develop a new theory on the understanding of 115 participants regarding the use of plant by-products as phytobiotic agents for emission reduction.

2.4 Data collection

One of the approaches in Grounded Theory research is the role of the researcher as the primary instrument for data collection, as well as the planner, analyst, data interpreter, and research report writer. There are two main methods used in the data collection process:

2.4.1 In-depth interviews

Data collection is conducted through interviews with unstructured questions, where the interviewer only has a general plan of questions or topics to be asked. These questions are broad and not a set of specific questions that must be asked in a fixed order or wording. Direct interviews are conducted with participants. To guide the interview process, the researcher prepares an interview guide containing key questions. All interview results are recorded in field notes, or if the interview is recorded via video or audio, the recordings must be transcribed into text format.

2.4.2 Literature review

The literature review is essential for uncovering various theories related to the research problem, serving as a reference for discussing the research findings. Both technical and non-technical literature play significant and diverse roles in the study.

a. Technical literature

This includes research reports, professional or disciplinary writings in the form of theoretical or philosophical papers, which serve as a background reference and as a comparative source for the data collected in this Grounded Theory study.

b. Non-technical literature

This includes biographies, diaries, reports, and other documents that can serve as primary data, complementing interviews and observations. This is achieved by reading, studying, and analyzing literature related to the use of plant by-products as phytobiotic agents for emission reduction, as well as reviewing various perspectives from research subjects, whether in the form of textbooks, articles, or modules.

2.5 Data analysis

In qualitative research using the Grounded Theory method, the data collection and analysis stages are interconnected and must be carried out alternately. Data analysis is the effort to systematically search for and organize interview notes and other materials to enhance the researcher's understanding of the case being studied and present it as findings to others. This can be done through coding, which is the process of breaking down data, creating concepts, and reorganizing them in a new way.

The procedure carried out in the data analysis stage, which forms the basis of the coding process, is continuous comparison and the posing of questions. The Grounded Theory research method emphasizes data validity through verification and uses coding as the primary tool for data processing. The process begins with coding and categorizing the data. There are three types of coding: open coding, axial coding, and selective coding. During this coding process, theoretical memos are written. Memos are not merely rigid ideas but are continuously changing and developing or being revised throughout the research process.

3. RESULTS

The production of horticultural and biopharmaca plants in the regency of Bone from the last three years is shown in Table 1.

Table 1. The production of horticultural and herbaceous plants in regency of Bone, South Sulawesi, Indonesia (kg/Ha) from 2021-2023

No.	Name	2021	2022	2023
1	Ginger	13.714.467	6.155.066	1.303.500
2	Galangal	1.345.061	2.036.954	2.036.954
3	East Indian Galangal	26.128	39.041	39.107
4	Turmeric	8.631.294	10.858.574	13.367.830
5	Lemon grass	489.192	1.256.731	1.811.215
6	Sweet Potato Plant	1.672.200	929.900	1.239.000

Source: Bone dalam Angka 2023 and 2024

Bone Regency covers an area of 4,559.00 km², with an average population density of 162 people per km². In 2021, the total population of Bone Regency was 801,775 people. As one of the regions located on the eastern coast of South Sulawesi, Bone Regency holds a strategic position in the trade of goods and services within Eastern Indonesia. Administratively, it consists of 27 districts, 328 villages, and 44 urban wards. The regency is situated 174 km east of Makassar City, positioned between 4°13'-5°06' S and 119°42'-120°30' E [4].

The Bone Regency is classified as a region with a moderate climate, characterized by humidity levels ranging from 95% to 99% and temperatures varying between 26℃ and 34℃. The region's topography includes mountains and hills, with numerous rivers flowing through their valleys. Surrounding these rivers are deep valleys, some of which contain water during the rainy season, with approximately 90 recorded water bodies. However, during the dry season, many of these rivers experience drought, except for major rivers such as the Walenae, Cenrana, Palakka, Jaling, Bulu-bulu, Salomekko, Tobunne, and Lekoballo rivers, which maintain their flow throughout the year [4].

Bone Regency, holds significant potential for livestock population expansion beyond Java Island. The local community greatly benefits from the agricultural sector, including livestock farming. The prospects for livestock development are highly promising, supported by the abundance of forage resources. The livestock subsector plays a crucial role in increasing per capita income in Bone Regency. Currently, Bone ranks as the fourth-largest regency in Indonesia in terms of livestock population at the national level.

The adoption of using herbaceous plants to livestock at Regency of Bone is shown in Table 2.

Table 2. Farmer's adaption of incorporating herbaceous plants for cattle feed in district Tanete Riattang and Tanete Riattang Timur, Regency of Bone, South Sulawesi, Indonesia

No.	Subject	Tanete Riattang	Tanete Riattang Timur
1	Feed for cattle	Elephant grass, rice straw (85% respondents)	Elephant grass, rice straw (80% respondents)
2	Herbaceous plants by product for cattle	a little bit of ginger (<5% of the respondents)	a little bit of ginger (<5% of the respondents)
3	Average feed consumed daily per head	7-8 kg (90% respondents)	7-8 kg (90% respondents)
4	Source of water	Natural water	Natural water
5	Type of medicine given for cattle	Wormzol + vaccination (90% respondents)	Wormzol + vaccination (90% respondents)
6	Technology of preparing phytobiotic formula	-	-
7	Training for preparing phytobiotic and the dose	-	-
8	The number of workers in cattle barns	1 (90% respondents)	1 (90% respondents)
9	The treatment for the feces	-	Fertilizer (<5% of the respondents)

The findings of this study indicated varying levels of awareness and understanding among farmers in the two selected districts in Bone Regency (Tanete Riattang and Tanete Riattang Timur) regarding the utilization of plant by-products as natural feed additives (Phyto-biotics) and their potential role in mitigating greenhouse gas emissions. While the concept of using Phyto-biotics for environmental benefits was relatively unfamiliar to most respondents, there was a significant awareness of using specific plant by-products, particularly ginger, as a feed additive to enhance palatability and livestock appetite.

Some recent studies have reported the success use of the individual herbal plants as methane reduction agents in cattle farming. Various plant-based feed additives, including turmeric, ginger, and lemongrass, have demonstrated potential in mitigating enteric methane emissions by modulating rumen fermentation, inhibiting methanogens, and enhancing alternative hydrogen utilization pathways [9]. Turmeric (Curcuma longa) is a widely studied medicinal plant known for its curcuminoids and essential oils, which exhibit antimicrobial, anti-inflammatory, and antioxidant properties. The primary bioactive compound in turmeric, curcumin, disrupts methanogen membrane integrity, thereby reducing their population in the rumen Additionally, curcumin shifts ruminal fermentation toward propionate production, a pathway that competes with methanogenesis for hydrogen utilization. By enhancing microbial diversity and stimulating fibrolytic bacteria, turmeric supplementation improves volatile fatty acid (VFA) profiles, which are essential for nutrient absorption and energy efficiency. The inclusion of 1.5% turmeric powder in cattle feed resulted in a 15-20% reduction in methane emissions, along with improved feed efficiency and immune function.

Ginger (*Zingiber officinale*) contains a variety of bioactive compounds, including gingerol, shogaol, and zingerone, which exhibit antimicrobial and anti-inflammatory properties. These compounds directly inhibit methanogenic archaea by interfering with their enzymatic activity, thereby reducing methane production [10]. Additionally, ginger promotes non-methanogenic fermentation pathways by increasing succinate and propionate synthesis, which serve as alternative hydrogen sinks. Another crucial mechanism of action is the modulation of fiber degradation rates; ginger slows down cellulose fermentation, leading to a more controlled release of fermentation gases [11]. Research conducted in Central Java involving the supplementation of dairy cattle diets with 2% ginger powder demonstrated an 18-22% reduction in methane emissions, along with improved milk fat content and overall gut health [12].

Lemongrass (*Cymbopogon citratus*), a tropical grass rich in citral, limonene, and polyphenols, has also been identified as an effective natural feed additive for methane reduction. Citral and limonene possess strong antimicrobial properties, which directly inhibit methanogenic archaea, thereby reducing the hydrogen-dependent formation of methane [13] . Furthermore, lemongrass modulates fermentation pathways by increasing the proportion of acetate and propionate, leading to more efficient energy metabolism. Studies conducted on Bali cattle farms, where lemongrass extract was incorporated at 1.8% of total dry matter intake (DMI), revealed a 25% decrease in methane emissions, coupled with improved feed conversion efficiency and resistance to gastrointestinal infections [14].

When used in combination, turmeric, ginger, and lemongrass exhibit synergistic effects, enhancing methane reduction through complementary mechanisms. Turmeric primarily targets methanogen suppression and hydrogen redirection, ginger modifies fiber degradation rates and fermentation kinetics, while lemongrass provides direct antimicrobial effects on methanogens and enhances overall rumen balance. *In vivo* experimental trial in beef cattle farm demonstrated that supplementing cattle diets with a mixture of turmeric (1%), ginger (1%), and lemongrass (1%) resulted in a 30-35% reduction in methane emissions without compromising feed digestibility [15].

In order to reduce the environmental impact from burning the by-product of sweet potato, it is necessary to utilize this as feed component for cattle. Some studies have reported the secondary compounds of this sweet potato by-product that is potential as methane reduction agent. Additionally, sweet potato by-product still have good nutritional values. Both the tubers and vines of sweet potato contain valuable bioactive compounds, including phenolic compounds, flavonoids, and resistant starch, which can influence rumen fermentation patterns and reduce enteric methane emissions. One of the primary ways sweet potato contributes to methane mitigation is through its high starch and low fiber composition. Unlike conventional roughage-based feeds, sweet potato tubers are rich in non-structural carbohydrates (NSC), particularly starch, which promotes propionate fermentation pathways in the rumen. The propionate pathway competes with methanogenesis for hydrogen (H_2) utilization, thereby reducing the availability of substrates for methane-producing archaea. Studies have shown that feeding high-starch diets, including sweet potato tubers, can lower methane emissions by up to 20-30% compared to high-fiber diets [16, 17] Additionally, the presence of resistant starch in sweet potato slows down fermentation, leading to a more controlled release of gases and a shift toward less methane-intensive fermentation end products [18].

Sweet potato vines, a by-product of tuber production, also exhibit methane mitigation potential due to their rich polyphenol and flavonoid content. Polyphenols, such as chlorogenic acid and anthocyanins, have been reported to possess antimicrobial properties that selectively inhibit methanogenic archaea in the rumen. The mechanism behind this suppression involves the disruption of coenzyme methyltransferase, an essential enzyme in methane synthesis. Research has indicated that feeding sweet potato vines at 15-20% of the total DMI can lead to a 12-18% reduction in methane production while maintaining or even improving fiber digestibility [16, 19].

Furthermore, the high beta-carotene content in sweet potato, particularly in orange-fleshed varieties, can indirectly contribute to methane reduction by enhancing rumen microbial balance and animal health. Beta-carotene is a precursor to vitamin A, which plays a crucial role in immune function and rumen epithelial integrity. A well-functioning rumen environment ensures optimal microbial activity, reducing the risk of dysbiosis, which can otherwise promote excessive hydrogen accumulation—a key precursor to methane synthesis. Additionally, sweet potato supplementation has been linked to improved feed conversion efficiency, meaning that cattle require less feed to achieve similar or greater weight gain, further contributing to a lower carbon footprint per unit of beef or milk produced. The integration of sweet potato into cattle feeding strategies aligns well with circular agriculture and sustainable farming systems. In regions where sweet potatoes are cultivated as a staple food crop, the utilization of by-products such as vines and unmarketable tubers can serve as an economically viable and environmentally friendly livestock feed. This dual benefit supports low-emission livestock production while promoting resource efficiency in mixed farming systems.

The majority of farmers demonstrated a limited understanding of the broader concept of Phyto-biotics and their environmental implications, reflecting a knowledge gap about the role of bioactive compounds in mitigating methane emissions. This is often constrained by a lack of access to technical information and training. In contrast, a minority of respondents showed a basic understanding of Phyto-biotics, often associating them with traditional practices rather than modern scientific approaches.

Interestingly, a significant proportion of farmers were familiar with the use of ginger (*Zingiber officinale*) as a feed additive, primarily to improve feed palatability and stimulate livestock appetite. However, they use this as individual substrate on the basis of their experience (traditional knowledge) of using ginger as herbal for human and they use this without knowing the proper dose. The farmers' application of ginger was largely limited to its immediate effects on feed intake, with little awareness of its secondary benefits, such as antimicrobial properties or potential reductions in ruminal methane production.

The variation in awareness levels between the two districts may be attributed to differences in access to agricultural extension services, exposure to innovation, and the educational background of the farmers. Districts with closer proximity to agricultural institutions or markets may benefit from greater dissemination of knowledge about advanced feeding practices, whereas more remote districts might rely predominantly on traditional methods. The prevalent use of ginger highlights an entry point for introducing the concept of Phyto-biotics to farmers. Extension programs and agricultural advisors can leverage farmers' familiarity with ginger to demonstrate its additional benefits, such as antimicrobial activity and methane reduction potential, thereby bridging the gap between traditional practices and scientific innovations [20]. Furthermore, the integration of other locally abundant plant by-products with similar properties, such as cassava or sweet potato leaves, could enhance the economic feasibility of adopting Phyto-biotics at scale. Sustaining the livestock sector is a way to elevate the sustainability for food supply [21].

Although extensive research has highlighted the benefits of herbal remedies in livestock farming, their implementation at the farmer level still encounters several challenges. One of the primary issues is the lack of knowledge regarding proper dosage and formulation. Farmers often struggle to determine the appropriate amount of herbal additives, which is crucial to avoiding negative effects. An overdose may disrupt metabolic functions in cattle, while an insufficient dosage may fail to deliver the intended health benefits. Additionally, the variability in the phytochemical composition of herbal plants poses another challenge [22]. Factors such as soil type, climate conditions, and cultivation methods can influence the concentration of bioactive compounds, making it essential for farmers to understand proper storage and processing techniques to maintain their efficacy. Moreover, the absence of standardized protocols in herbal remedy preparation further complicates their use [23]. Without uniform guidelines, different farmers may achieve inconsistent results, reducing the reliability of herbal treatments. To address these issues, further research is needed to develop standardized, scientifically validated formulations that ensure both effectiveness and safety in livestock applications.

The limited adoption of Phyto-biotics in cattle feed among farmers is influenced by a combination of economic, technical, informational, and infrastructural barriers. From an economic perspective, Phyto-biotics often entail a higher initial investment compared to conventional feed additives, making them less attractive to farmers operating under financial constraints. The cost-benefit trade-off is a critical determinant in decision-making, as many smallholder farmers prioritize short-term economic viability over long-term sustainability. Studies indicate that financial limitations significantly hinder the adoption of innovative feed technologies, as farmers often lack access to credit or subsidies that could mitigate the initial costs [24]. Without clear and immediate economic incentives, the perceived financial risk associated with Phyto-biotic adoption discourages widespread implementation.

Furthermore, the lack of technical knowledge presents a significant impediment to adoption. The effective utilization of Phyto-biotics requires an understanding of appropriate dosages, feeding strategies, and their interactions with other dietary components. Many farmers, particularly in developing regions, have limited access to structured training programs or extension services that provide this specialized knowledge. Knowledge gaps in livestock nutrition and feeding practices prevent the widespread adoption of alternative feed additives, including Phyto-biotics. This results in uncertainty regarding efficacy and proper application, thereby reinforcing resistance to change [25].

In addition to technical limitations, a lack of awareness regarding the potential benefits of Phyto-biotics further constrains their adoption. Farmers may not fully understand the role of these natural additives in improving cattle health, enhancing feed efficiency, and reducing environmental emissions. This issue is exacerbated by inadequate dissemination of scientific research through extension programs, agricultural cooperatives, and governmental initiatives [26]. Without targeted awareness campaigns and evidence-based demonstrations, farmers may not be able to recognize the long-term advantages of Phyto-biotics. Additionally, infrastructural challenges play a crucial role in limiting accessibility to Phyto-biotic feed additives. The supply chain for these products is often underdeveloped in rural areas, where distribution networks, transportation, and storage facilities are inadequate. As a result, farmers face difficulties in procuring Phyto-biotics consistently, which discourages their integration into feeding systems. The lack of a stable supply chain and reliable market access further diminishes the feasibility of adopting Phyto-biotics on a large scale [25]. To address these challenges, a comprehensive approach is necessary, integrating economic incentives, capacity-building initiatives, awareness programs, and infrastructure development. Policymakers, researchers, and industry stakeholders must collaborate to provide financial support mechanisms such as subsidies or credit schemes, enhance extension services for knowledge dissemination, and invest in supply chain improvements. By overcoming these barriers, the adoption of Phyto-biotics in cattle feed can be significantly improved, leading to enhanced livestock productivity, reduced environmental impact, and greater sustainability in the livestock sector.

It is necessary to enhance farmers' knowledge and application through various strategic measures to optimize the utilization of herbal remedies in livestock production. One fundamental approach is the implementation of scientific-based training and mentoring programs. Government agencies, academic institutions, and livestock extension specialists should facilitate regular training sessions to educate farmers on the classification of herbal plants, extraction techniques, formulation methods, and appropriate dosage administration for beef cattle. Additionally, the integration of technology in the formulation and processing of herbal remedies can significantly enhance the stability and bioavailability of active compounds. The application of simple yet effective technologies, such as fermentation and hot-water extraction, can improve the efficacy and shelf-life of herbal preparations administered to livestock [10, 27]. Collaborative efforts with research institutions and universities are crucial in advancing the scientific validation and standardization of herbal remedies. Strengthening synergies between farmers, researchers, and academic experts will facilitate the development of evidence-based herbal formulations while ensuring compliance with livestock health and safety standards.

The Indonesian government has regulated the use of feed additives, including those derived from herbal ingredients, through various regulations issued by the Ministry of Agriculture. These regulations aim to ensure that all feed ingredients used in the livestock industry meet established safety and quality standards.

One of the key regulations is Minister of Agriculture Regulation No. 22 / Permentan / PK.110 / 6 / 2017 on Feed Registration and Distribution. This regulation sets out the technical and administrative requirements that feed producers, including those producing herbal-based feed, must meet before their products can be registered and marketed in Indonesia [28]. Government Regulation No. 26 of 2021 on the Implementation of the Agricultural Sector replaces Government Regulation No. 78 of 1992 on Veterinary Drugs. This regulation includes provisions regarding minimum technical and quality standards for feed, including the use of additives such as herbal ingredients in livestock feed [29]. The objective is to ensure that all feed additives, including herbal-based ones, comply with the established standards to guarantee animal health and the safety of animal-based food products for consumers.

Governmental policies and incentives play a fundamental role in facilitating the adoption of Phyto-biotics in livestock production by addressing financial, technical, infrastructural, and regulatory barriers that hinder their widespread implementation. One of the primary economic constraints faced by farmers is the higher initial cost associated with Phyto-biotic-based feed additives compared to conventional alternatives. To mitigate this challenge, policymakers can introduce targeted financial interventions such as direct subsidies, tax exemptions, and low-interest credit schemes, thereby enhancing the affordability and accessibility of Phyto-biotics. By reducing the cost burden on farmers, these financial mechanisms can incentivize the transition from synthetic additives to phytogenic compounds, contributing to more sustainable livestock production systems [24].

Beyond financial interventions, the lack of technical knowledge among farmers regarding the efficacy, appropriate dosage, and application of Phyto-biotics remains a critical impediment to their adoption. In this regard, government-supported extension services, training programs, and knowledge dissemination initiatives are essential in bridging the existing knowledge gap. The implementation of farmer field schools, demonstration farms, and mobile advisory units can facilitate experiential learning and practical exposure, allowing farmers to observe firsthand the benefits of Phyto-biotics in enhancing livestock health, improving feed efficiency, and mitigating environmental impacts. Moreover, investments in publicly funded research can strengthen the scientific basis for Phyto-biotic use by generating empirical evidence on their effectiveness, mode of action, and potential synergies with locally available feed resources. Collaboration between research institutions, universities, and government agencies can further support the development of region-specific Phyto-biotic formulations tailored to the nutritional requirements of different livestock species, ensuring their practical applicability in diverse production systems. Infrastructure development is another crucial aspect that influences the adoption of Phyto-biotics, particularly in rural and remote areas where logistical constraints limit farmers' access to innovative feed additives [30, 31]. Government interventions aimed at improving supply chain efficiency, enhancing transportation networks, and investing in feed processing and storage facilities can facilitate the consistent availability of high-quality Phyto-biotics in the market. Policies that promote domestic production of Phyto-biotics from locally sourced plant materials can further strengthen supply chain resilience while reducing reliance on costly imports. By fostering a conducive regulatory environment that supports Phyto-biotic standardization, certification, and quality assurance, governments can build farmer confidence in these feed additives and prevent the proliferation of substandard or adulterated products in the market.

Regulatory policies also play a pivotal role in shaping the adoption trajectory of Phyto-biotics, particularly in the context of antimicrobial resistance (AMR) mitigation and climate change adaptation. The progressive phasing out of antibiotic growth promoters (AGPs) in livestock production, as mandated by regulatory frameworks in many countries, creates an opportunity for Phyto-biotics to serve as natural alternatives [32]. Governments can reinforce this transition by integrating Phyto-biotic adoption into national antimicrobial stewardship programs and providing incentives for farmers who comply with antibiotic reduction targets. Furthermore, given the increasing global emphasis on reducing livestock-related methane emissions, Phyto-biotic-based feeding strategies can be incorporated into national climate policies and sustainable agriculture initiatives. The implementation of carbon credit schemes, wherein farmers utilizing Phyto-biotics to reduce methane emissions receive financial incentives, can serve as an innovative policy mechanism to align environmental objectives with economic incentives.

4. CONCLUSIONS

The livestock farming community in Bone Regency still experiences a significant knowledge gap regarding the benefits of utilizing herbal plants, particularly the introduction of purple sweet potato plant waste, which is abundantly available in the area. There is a lack of understanding on how to formulate the by-product of the herbaceous plants and the horticultural plants appropriately to ensure they do not have adverse effects on beef cattle. A comprehensive and continuous assistance and monitoring is required to ensure that in the future the local farmers are able to apply the by-products as feed additive for beef cattle to support the reduction in environmental foot print from livestock farm. It is recommended that the government and the universities collaborates intensively to support the development training and capacity building for the local farmers and also provide a sustainable technical assistance in developing the cattle farm in South Sulawesi.

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