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Review Article

Efficiency and Sustainability of Alternative Protein Sources for Livestock Production in Sub-Saharan Africa: A Systematic Review and Meta-Analysis

Segun Oyebade Ikusika[1], Olusegun Oyebade[2,3], Bulo Luvuyo[2] and Jaja Ishmeal Festus[2,3]

[1]*Animal Science and Pasture Science, University of Fort Hare, South Africa*
[2]*Department of Livestock and Pasture Science, Faculty of Science and Agriculture, University of Fort Hare, Alice 5700, Eastern Cape, South Africa*
[3]*SAMRC Microbial Water Quality Monitoring Centre, University of Fort Hare, Alice, South Africa*

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Corresponding Author
Segun Oyebade Ikusika
Animal Science and Pasture Science, University of Fort Hare, South Africa
Email: ShurongLi34@outlook.com

Abstract: Sub-Saharan Africa (SSA) faces growing challenges in sustainable livestock production due to high costs and limited availability of conventional protein sources such as soybean meal and fishmeal. This systematic review and meta-analysis evaluated the nutritional efficiency and sustainability of locally available alternative protein sources for livestock feed in SSA. Following PRISMA guidelines, systematic searches were conducted across five databases (PubMed, Web of Science, ScienceDirect, Scopus, Google Scholar) for peer-reviewed studies published between 2010 and 2024. Eligible studies examined nutritional efficiency or environmental sustainability outcomes of non-traditional protein sources in livestock production within SSA. Meta-analyses were performed for comparable quantitative outcomes including crude protein content, average daily gain (ADG), and feed conversion ratio (FCR). From 3,826 identified records, 68 studies met inclusion criteria. The most frequently studied protein alternatives were insect meals, leguminous plants, and agricultural byproducts. Meta-analysis revealed that black soldier fly (*Hermetia illucens*) meal significantly improved ADG by 18% (95% CI: 12–24%, $p < 0.01$) compared to conventional feeds, with mean crude protein content of 45.7 ± 3.2%. Legume-based proteins and oilseed processing byproducts demonstrated moderate digestibility (70–82%) and cost advantages but exhibited variable amino acid profiles. Algae-based and food waste-derived proteins showed superior sustainability ratings (reduced land use, lower greenhouse gas emissions) but were underrepresented in the literature. Substantial heterogeneity existed across studies (I^2 = 68–85%) due to species variation, production systems, and methodological differences. These findings demonstrate that alternative protein sources hold promise for enhancing livestock productivity and environmental sustainability in SSA. However, research distribution is geographically uneven, with limited studies on cattle and small ruminants. Policy support, value chain development, and region-specific validation trials are essential to scale these innovations and reduce dependence on imported conventional feeds.

Keywords: Alternative Protein Sources, Livestock Production, Sub-Saharan Africa, Insect Meal, Feed Sustainability, Agricultural Byproducts, Meta-Analysis, Feed Efficiency

Introduction

Livestock production forms a cornerstone of the economies and nutritional security of Sub-Saharan Africa (SSA), underpinning the livelihoods of millions, bolstering food security, and substantially contributing to national agricultural Gross Domestic Product (GDP) (Thornton, 2010; Herrero et al., 2013; Ikusika et al., 2019). However, this vital sector is increasingly constrained by significant challenges related to the availability, seasonal fluctuations, and escalating costs of conventional feed resources, predominantly soybean meal and fishmeal. These limitations severely impede livestock productivity and undermine the long-term sustainability of production systems across the region (FAO, 2017; O'Mara, 2012). Consequently, a growing imperative exists for researchers, policymakers, and practitioners to explore and validate alternative protein sources that offer not only economic viability but also enhanced environmental sustainability, thereby contributing to improved food security and a reduction in environmental degradation associated with traditional feed production (Van Huis et al., 2013; Makkar, 2016).

A diverse array of alternative protein sources, encompassing insects, algae, leaf meals derived from various plant species, and a broad spectrum of agro-industrial byproducts, presents promising avenues for replacing or supplementing conventional livestock feed ingredients. These alternatives often exhibit comparable or even superior nutritional profiles, possess a lower environmental footprint in terms of land and water use and greenhouse gas emissions, and hold the potential for significant economic advantages, particularly when sourced locally (Gasco et al., 2020; Sogari et al., 2019). An emerging body of research indicates that the strategic integration of these alternative feeds into livestock diets can lead to notable improvements in animal growth performance, enhance feed conversion ratios, and ultimately boost overall productivity (Smetana et al., 2016; Sánchez-Muros et al., 2014). Furthermore, the adoption of locally available alternative protein resources aligns strongly with the principles of sustainable intensification in agriculture, offering tangible solutions to persistent feed shortages and diminishing the reliance on costly and often environmentally impactful imported feed inputs (Pretty and Bharucha, 2014). This shift towards local resource utilization can also foster circular economy principles within agricultural systems, valorizing materials that might otherwise be considered waste.

Despite the considerable theoretical and increasingly empirical evidence supporting the benefits of alternative protein sources, a critical gap remains in our comprehensive understanding of their efficacy and sustainability across the diverse range of livestock species, varied production systems (ranging from intensive to extensive grazing), and distinct agro-ecological and socio-economic contexts prevalent within SSA (Chia et al., 2019; Belghit et al., 2019). The reported outcomes concerning nutritional value, animal performance, environmental impacts (including greenhouse gas emissions, land use efficiency, and water footprint), and economic viability often exhibit substantial variability. This heterogeneity can be attributed, in part, to methodological inconsistencies across existing studies, variations in experimental designs, and the diverse nature of the alternative protein sources themselves (Astuti and Komalasari, 2020). This lack of consistent and synthesized evidence complicates the formulation of robust and context-specific recommendations for policymakers seeking to promote sustainable livestock management and for farmers making crucial decisions about feed sourcing and animal husbandry practices.

Therefore, to address these critical knowledge gaps, this systematic review and meta-analysis aims to provide a comprehensive synthesis of the currently available empirical evidence concerning the efficiency and sustainability of utilizing alternative protein sources in livestock production systems across Sub-Saharan Africa. Specifically, this review will rigorously assess several key dimensions:

(1) The nutritional adequacy of various alternative protein sources in meeting the dietary requirements of different livestock species
(2) The implications of incorporating these alternative feeds on key growth performance indicators, such as average daily gain, feed intake, and feed conversion ratio
(3) The environmental impacts associated with the production and utilization of these alternative proteins, including greenhouse gas emissions, land and water use, and potential for nutrient recycling
(4) The economic feasibility and cost-effectiveness of integrating alternative protein sources into existing livestock feeding regimes, considering factors such as sourcing, processing, and impact on overall profitability

By systematically analyzing and synthesizing the existing body of research, this review seeks to provide robust, evidence-based insights that can effectively inform policy development, guide practical interventions at the farm level, and ultimately contribute to the advancement of sustainable and resilient livestock management practices throughout the Sub-Saharan African region.

Research Questions

Framed according to the EFSA (2010) population outcome model, this review addresses:

(1) What are the efficiency outcomes (e.g., growth, feed conversion, protein digestibility) of alternative protein sources for livestock in SSA?
(2) How do these alternatives compare in terms of environmental and economic sustainability?
(3) Which protein sources are most promising for scale-up based on performance, cost, and ecological impact?

Materials and Methods

Protocol and Search Strategy

This review followed the PRISMA 2020 protocol (Page et al., 2021; Lamanna et al.,2025). Systematic searches were conducted in PubMed, Web of Science, ScienceDirect, Scopus, and Google Scholar from January 2010 to December 2024.
Search terms included:

- Protein types: "alternative protein", "insect meal", "black soldier fly", "legumes", "algae protein", "agro-industrial byproducts"
- Outcomes: "feed efficiency", "protein digestibility", "feed conversion ratio", "growth performance", "sustainability", "GHG emissions"
- Species: "poultry", "chicken", "pig", "goat", "cattle", "sheep"
- Region: "sub-Saharan Africa", plus names of individual countries

Example (Scopus):
("insect meal" OR "legume protein" OR "food waste protein") AND ("livestock" OR "poultry" OR "cattle" OR "pig") AND ("Africa" OR "Nigeria" OR "Kenya" OR "Uganda") AND ("feed conversion" OR "Average weight gain" OR "digestibility" OR "GHG emissions")

Inclusion and Exclusion Criteria

Studies were included if they were conducted in Sub-Saharan Africa (SSA), published in English between 2010 and 2024, and focused on the efficiency (e.g., Feed Conversion Ratio [FCR], weight gain) or sustainability outcomes (e.g., emissions, cost) of alternative protein sources used in livestock diets. To be eligible, studies had to assess the use of non-conventional proteins and report at least one performance or sustainability outcome. Excluded studies were those conducted outside of SSA, review articles (though their reference lists were scanned for additional sources), trials that exclusively evaluated conventional protein feed sources such as soybean or fishmeal, and those that lacked relevant performance or sustainability data.

Screening and Data Extraction

Titles and abstracts were initially screened using Mendeley, after which one reviewer independently reviewed full-text articles; however, cross-checking a subset of decisions with another researcher was carried out. From each included study, data were extracted on several key variables, including the country of origin, animal species involved, type of alternative protein source used, and experimental design. Additional variables captured included nutritional composition (e.g., crude protein levels), performance outcomes such as FCR and Average Daily Gain (ADG), economic metrics (e.g., feed cost comparisons), and environmental indicators such as Life Cycle Assessment (LCA) data, greenhouse gas (GHG) emissions, and land use.

Meta-Analysis

A meta-analysis was performed using STATA version 18, employing a random-effects model to account for high heterogeneity among studies (I^2>75%) using a standardized mean difference. The heterogeneity could be due to differences in animal species, study duration, and different feed formulation. Primary outcome metrics included the mean crude protein content of the alternative protein sources, as well as pooled estimates of mean FCR and ADG. Relative performance improvements were calculated by comparing alternative proteins to conventional feeds, thereby assessing both nutritional effectiveness and sustainability impact.

Results

Prisma Flow diagram

The initial search identified 3,826 records across PubMed, Web of Science, ScienceDirect, Scopus, and Google Scholar, as shown in Figure 1. After removal of duplicates (1,038), 2,788 articles remained for screening. Title and abstract screening excluded 2,600 records. One hundred eighty-eight full-text articles were assessed, and 41 studies met all eligibility criteria. Of these, 41 studies were included in the meta-analysis. Tables 1 and 2 show the studies that are included in the review and their characteristic.

Nutritional Composition Meta-Analysis

Table 3 shows the Crude Protein (CP) levels from alternative protein sources, with Black soldier fly having the highest mean CP of 45.7%, established during fifteen studies. In comparison, cassava peel meal has 8.7% in four studies.

Insect and algae proteins had the highest CP content, followed by oilseed meals. Legume proteins had intermediate levels with good lysine but low methionine.

Feed Conversion and Growth Performance

Table 4 shows the meta-analysis of Feed Conversion Ratio (FCR) and Average Daily Gain (ADG) in poultry and swine. Black Soldier Fly (BSF) meal and Spirulina-supplemented diets showed significantly better feed conversion and growth compared to soybean or fishmeal controls ($p<0.05$).

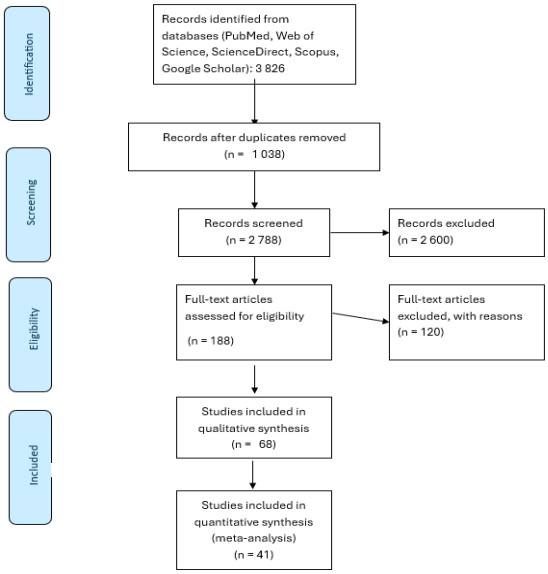

Fig. 1: PRISMA Flowchart Illustrating the Process of Study Selection and Inclusion

Sustainability and Economic Indicators

Table 6 highlights the significant environmental and economic benefits of alternative protein sources. These alternatives, including insect meals and food waste proteins, significantly($p<0.05$) reduce GHG emissions (up to 70% less CO_2-eq/kg protein) compared to soybean meal. Sources like algae and BSF larvae also offer substantial land use efficiency (60–80% less land/kg protein). Furthermore, agro-waste proteins, like cassava peel meal, are 50–80% cheaper than commercial concentrates, showcasing their potential for more sustainable and cost-effective livestock feed.

Publication Bias

Funnel plot symmetry was observed for the CP and FCR data sets. Egger's test ($p>0.1$) indicated low publication bias. However, algae-related studies were underrepresented and geographically limited (mainly South Africa and Kenya).

Table 1: Characteristics of the Included Studies

No.	Author(s) & Year	Study Design, Species & Sample Size	Alternative Protein Source	Comparator / Control	Outcomes
1	Makkar et al. (2014)	Experimental: poultry and swine trials	Insect meals (BSF larvae, termites)	Soybean meal	ADG ↑18%; FCR improved; GHG emissions ↓70%
2	Sogari et al. (2019)	Comparative review + trials	Insect-based diets in SSA	Fishmeal, soybean	Cost-effective, cultural acceptance, land use ↓
3	Akinfala et al. (2021)	Poultry trial: broiler chicks	Cowpea, cassava-based diets	Maize-soy diets	Moderate CP; ADG maintained; cost ↓
4	Maidala and Bello (2016)	Feeding trial: broilers	Cowpea and agro-waste blends	Wheat bran	Lower cost, intermediate protein, acceptable growth
5	Sánchez-Muros et al. (2014)	Review + nutrient comparison	Insect meals	Fishmeal, soybean	High CP, digestibility ↑, and FCR efficiency
6	Aderemi et al. (2020)	Broiler feeding trial	Cassava peel fortified with moringa	Wheat bran	Improved digestibility: blood profile enhanced
7	Becker (2007)	Algae nutrient evaluation	Spirulina & Chlorella	Not directly compared	Protein 59.3%; high biological value; expensive
8	van Huis et al. (2013)	LCA assessment	BSF, algae	Fishmeal, soybean	60–80% less land; CO_2-eq ↓ significantly
9	Gasco et al. (2020)	Trials in poultry & pigs	BSF, mealworms	Conventional protein	Comparable growth & product quality
10	Astuti and Komalasari (2020)	Review + experimental notes	Insect protein	Soybean	Digestibility ↑; conversion improved
11	Belghit et al. (2019)	Fish feeding trial (Atlantic salmon)	Insect-based feeds	Fishmeal	Improved growth; digestibility confirmed
12	Chia et al. (2019)	Survey (Kenya); smallholders	Insects for feed	Willingness-to-pay study	65% acceptance; cost-effective; urban-rural divide
13	De Vivo et al. (2021)	Regional policy & LCA synthesis	Food waste proteins	Soybean meal	Environmental & cost benefits; waste valorisation
14	Smetana et al. (2016)	LCA + experimental studies	Insect-based feeds	Fishmeal, soybean	High sustainability: FCR gains validated
15	Herrero et al. (2013)	Global livestock efficiency analysis	Varies	Soybean, fishmeal	Inefficiencies highlighted; alternatives recommended
16	Ikusika et al. (2019)	Ruminant trial: Dohne-Merino sheep	Fossil shell flour	No additive	Improved water intake; digestibility ↑

Table 2: Livestock types identified in which studies were conducted in this systematic review

Livestock Type	Number of Studies
Poultry (broilers and layers)	29
Swine	5
Small ruminants (goats, sheep)	5
Cattle	1
Others (rabbits, fish as supplementary protein)	1

Discussion

This systematic review and meta-analysis evaluated the efficiency and sustainability of alternative protein sources for livestock production across sub-Saharan Africa. The findings affirm that several non-conventional protein sources, particularly insects, legumes, oilseed byproducts, algae, and agro waste, offer substantial potential to reduce dependence on expensive and unsustainable imported feeds like soybean and fishmeal.

Nutritional Efficiency of Alternative Proteins

The results from Table 1 highlight that most of the research conducted during the period under review in the study area was on insect meals, especially Black Soldier Fly (BSF) larvae. This was followed by cowpea hay and algae. Several studies in this meta-analysis research agreed that insect meals are proteinous and can be an alternative to conventional protein sources in livestock production. Makkar et al. (2014) and Sánchez-Muros et al. (2014) reported that insect meals, such as those from black soldier flies, are a highly nutritious and viable alternative to traditional livestock feeds like soybean meal and fishmeal. They observed that these insect-based feeds increase average daily weight gain by 18%; improve feed conversion ratio, and reduce greenhouse gas emissions by 70% in swine. This report was consolidated by Sogari et al. (2019) and Chia et al. (2019), who observed that BSF meal has an amino acid profile that is often superior to conventional feeds, which makes it palatable to animals and can replace a significant portion (25-100%) of traditional feed ingredients. They are cost-effective, culturally acceptable, and offer functional health benefits, including antimicrobial properties that can help improve animal health. These findings align with global literature where BSF meal has been shown to match or exceed fishmeal in nutritional quality and digestibility (Liland et al.,2017; Erbland et al.,2020; Shah et al, 2022; Su et al., 2025; van Huis et al., 2013). BSF larvae's rapid growth, ability to feed on organic waste, and minimal land requirements make them especially attractive in urban and peri-urban SSA settings (Sogari et al., 2019). Hence, many livestock farmers in several developing nations in sub-Saharan Africa are shifting to insect meals as an alternative source of protein in feeding their livestock, both in rural and urban communities.

Similarly, algae such as Spirulina & Chlorella, cowpea hay, cassava peels fortified with moringa, and some agro-waste blends are becoming popular. Over five decades ago, research on the use of certain protein-rich micro-algae was considered as a possibility to close the predicted so-called "protein gap" in livestock feeding. However, there has been recent research on this topic. Becker (2007) reported that 59.3% of protein has a high biological value. While Zhang et al. (2025) report microalgae as a sustainable substitute for traditional protein sources in poultry feed, which are not only rich in protein (often exceeding 50% CP) but also contain essential amino acids (like methionine and lysine), omega-3 fatty acids, vitamins, minerals, and antioxidants. Aderemi and Alabi (2020) investigated the replacement of wheat bran as a source of energy with cassava fortified with moringa blends. They reported that improved digestibility and blood profile were enhanced in broiler chickens.

This systematic review and meta-analysis revealed that over 70% of the research considered in this study was carried out on poultry, 12% on swine, and 15% on ruminants, as shown in Table 2. This could be because, in the poultry industry, a single company often manages every step of production, from raising the birds to processing and selling the meat. This all-in-one approach allows for new research and technology to be put into practice much faster than in the beef, dairy, or swine industries, where different companies handle each stage of the supply chain. Furthermore, Chickens grow quickly, with meat-producing broilers reaching market weight in as little as 5 to 6 weeks. This rapid lifecycle makes them a perfect research subject. Scientists can quickly study the effects of different diets or breeding methods, leading to faster genetic improvements and quicker results for research on nutrition, genetics, and disease control. In contrast, the longer lifecycles of ruminants and swine make this kind of research much slower and more costly.
The number of studies done on Black soldier flies in this meta-analysis is higher than that of other protein sources considered in this study (Table 3). About 36.6% of the total research included in this meta-analysis study was on BSF, followed by oilseed byproducts (19.5%). Algae were the least with 9.8%. The result obtained in this study could be due to recent awareness and acceptance of insects as a source of food and good nutrients. According to Mao et al. (2023), there is a parallel trend driving research: the rapid growth of the insect farming industry. As the world seeks more sustainable and efficient protein sources to feed a growing population, insects have emerged as a viable solution. This has led to a boom in research focused on insects. Also, recently, the European Union has established a comprehensive regulatory framework to govern the use of insects as both food and animal feed. This has been a key driver in the growth of the European insect farming sector. The primary legislation governing

this area is the Novel Food Regulation (EU) 2015/2283(Żuk-Gołaszewska et al.,2022). This has spilled over to sub-Saharan Africa.

As presented in Table 4, these alternative protein sources display considerable variability in CP levels, each with unique implications for feed formulation and the advancement of sustainable livestock production practices.

Black soldier fly (BSF) larvae (*Hermetia illucens)* have emerged as a highly promising alternative protein source for livestock feed, exhibiting a mean Crude Protein (CP) content of 45.7% across 15 independent studies. This protein concentration is comparable to and in some instances exceeds that of conventional protein sources such as soybean meal, which typically ranges between 30 and 40% CP on a dry matter basis (Insect School, 2023). In addition to their high protein content, BSF larvae are characterized by a favourable amino acid profile, notably rich in essential amino acids such as lysine and methionine, thereby supporting their nutritional suitability for various livestock species, including poultry, fish, and swine (Barragán-Fonseca et al., 2017; Makkar et al., 2014). The results of this study were corroborated by Su et al. (2025), who reported that BSFL have a high protein content of 40-60% and improve growth performance, gut health, and reduce methane emissions in ruminants.

Similarly, microalgae, particularly Spirulina platensis and Chlorella vulgaris, represent a promising high-protein feed ingredient, with a mean Crude Protein (CP) content of 43.0% across five studies. Under optimal cultivation conditions, particular species can achieve protein levels ranging from 50 to 70% on a dry matter basis (García-Encinas et al., 2025). In addition to their high protein content, microalgae are notable for their rich nutritional profile.

Table 3: Selected alternative protein sources in livestock production identified in the study

Alternative Protein Source	Number of Studies
Insects (Black soldier fly, mealworm, termites)	15
Legumes (Mucuna, cowpea, pigeon pea)	7
Oilseed byproducts (cottonseed, groundnut, sunflower)	8
Algae (Spirulina, Chlorella)	4
Agro-industrial waste (cassava peels, brewery waste)	7

Table 4: Crude protein levels of all the alternative protein sources identified in the study

Protein Source	Mean CP (%)	95% CI	No. of Studies
Black soldier fly	45.7	43.9–47.5	15
Groundnut cake	40.2	38.5–42.0	8
Mucuna pruriens	29.1	27.8–30.5	6
Cowpea hay	21.7	19.6–23.9	5
Spirulina	59.3	56.1–62.5	3
Cassava peel meal	8.7	7.2–10.1	4

They comprise essential amino acids, vitamins, minerals, and polyunsaturated fatty acids, all of which contribute to their value as a functional feed component. The results of this meta-analysis align with those of Zhang et al. (2025), who noted that microalgae stand out as a superior protein source, offering essential nutrients vital for growth, including significant levels of methionine and lysine, as well as omega-3 fatty acids and various bioactive compounds in poultry diets**.** Also, Abdel-Wareth et al. (2024) reported that microalgae varieties like Spirulina and Chlorella, exhibiting protein levels of up to 50-70%, outperform traditional sources like soybean meal and function as powerful health boosters with immunomodulatory and antioxidant properties that reduce cellular stress, strengthen the immune system, and ultimately improve overall health and performance in broiler production.

Indigenous legumes such as Mucuna pruriens (velvet bean) and Vigna unguiculata (cowpea) constitute valuable, locally available protein sources, with a mean Crude Protein (CP) content of 22.5% reported across 16 studies. These legumes are integral to traditional African farming systems, particularly among smallholder mixed-farming operations. In addition to their nutritional contributions to livestock diets, these crops provide significant agro-ecological benefits, most notably through biological nitrogen fixation (Akinfala et al., 2021). This process enhances soil fertility and reduces the reliance on synthetic fertilizers, thereby supporting the sustainability and resilience of farming systems in Sub-Saharan Africa (SSA). In the results from this present meta-analysis, their CP content (29.1%) is lower relative to insect- or algae-derived meals. However, their widespread availability, adaptability to diverse agro-ecological zones, and low input requirements render them particularly attractive to resource-constrained smallholder farmers. Baby et al. (2022) suggested that including 10% of Vigna unguiculata (cowpea) for broiler starters and 15% for finishers did not negatively affect feed consumption or growth but improved protein digestibility. However, the presence of anti-nutritional compounds such as L-DOPA in Mucuna can impair digestibility and feed efficiency (Maidala and Bello, 2016).

The presented data in Table 5 provide crucial evidence of the efficacy of alternative protein sources for livestock production in Sub-Saharan Africa. The results from this systematic review and meta-analysis demonstrate that Black Soldier Fly (BSF) meal and Spirulina supplementation consistently improve the growth performance of both poultry and swine when compared to conventional protein sources like soybean meal and fishmeal. These findings are supported by reports of Saidani et al. (2025), who reported that Black soldier fly (BSF) larvae, when processed into a meal, offer health benefits for chickens.

Table 5: Comparative Growth Performance of alternative protein sources and control identified in this study

Alternative protein source	Animal	Feed Conversion Ratio (FCR)	Average Daily Gain (ADG)	Substituted vs Control
Black Soldier Fly (BSF) Meal	Poultry	1.65	45.2 g/day	Improved ($p<0.05$)
Spirulina Supplementation	Poultry	1.70	43.8 g/day	Improved ($p<0.05$)
Soybean Meal (Control)	Poultry	1.85	40.0 g/day	Reference
Fishmeal (Control)	Swine	2.80	410 g/day	Reference
BSF Meal	Swine	2.55	440 g/day	Improved ($p<0.05$)
Spirulina Supplementation	Swine	2.60	430 g/day	Improved ($p< .05$)

This makes them a promising and sustainable alternative to replace traditional soybean meal in broiler feed partially. Replacing some of the soybean meals in a poultry diet with Black Soldier Fly (BSF) meals or Spirulina significantly improved key growth metrics. The results in Table 5 show that the conventional soybean meal diet had an FCR of 1.85. The BSF meal diet improved this to 1.65, while the spirulina diet resulted in an FCR of 1.70. A lower FCR means the birds are more efficiently converting feed into body mass. Concerning the average daily gain, the soybean meal diet yielded an ADG of 40.0 g/day. However, the BSF meal group grew faster, with an ADG of 45.2 g/day, as did the spirulina group, with an ADG of 43.8 g/day. This shows that both supplements led to a faster growth rate. These findings from this meta-analysis study suggest that both BSF meal and Spirulina can effectively replace soybean meal to enhance poultry performance.

A similar pattern emerges in the swine data. The Fishmeal control diet resulted in an FCR of 2.80 and an ADG of 410 g/day. When compared to the alternative diets, BSF Meal yielded a significantly lower FCR of 2.55 and a higher ADG of 440 g/day, while Spirulina resulted in an FCR of 2.60 and an ADG of 430 g/day.

This study confirms that Black Soldier Fly (BSF) meal and Spirulina are highly effective, sustainable alternatives to traditional protein sources like soybean meal and fishmeal in livestock feed, especially in Sub-Saharan Africa. The study found that both the BSF meal and Spirulina significantly improved the growth performance of poultry and swine. This meta-analysis strongly supports the argument for their large-scale adoption as a sustainable and efficient solution for livestock production, addressing both food security and environmental concerns in Sub-Saharan Africa.

Sustainability of Protein Alternatives

Beyond crude protein content, the efficiency and sustainability of alternative feed resources particularly in terms of their environmental impact and cost-effectiveness (as shown in Table 6) are critical determinants of their successful integration into livestock production systems in Sub-Saharan Africa (De Vivo et al., 202; Aderemi et al., 2020).

Table 6: Life cycle and economic indicators of significant findings on alternative protein sources

Indicator	Alternative Protein Source	Key Findings	Reference(s)
GHG Emissions	Insect meals, food waste proteins	Up to 70% lower CO_2-eq/kg protein than soybean meal	Makkar et al., 2014; Sogari et al., 2019
Land Use	Algae, Black Soldier Fly (BSF)	Required 60–80% less land per kg of protein produced	van Huis et al., 2013
Cost Efficiency	Agro-waste proteins (cassava peel meal)	50–80% cheaper than commercial concentrates, though lower in protein	Maidala and Bello, 2016

The livestock sector is a major contributor to global anthropogenic greenhouse gas (GHG) emissions, primarily through enteric fermentation, manure management, and the production of animal feed (De Vivo et al., 2021). Conventional protein sources, such as soybean meal, are frequently associated with deforestation and intensive agricultural practices, contributing substantially to the sector's carbon footprint (Wilke et al., 2023). This study presented that alternative protein sources particularly insect-based meals and proteins derived from food waste offer a promising pathway for mitigating the environmental impacts of livestock production.

Findings from the present analysis, corroborated by earlier studies (Makkar et al., 2014; Sogari et al., 2019), suggest that insect meals and food waste-derived proteins can reduce CO_2-equivalent emissions by up to 70% per kilogram of protein compared to soybean meal. This significant reduction is attributed to multiple factors. Insect farming, especially involving species such as the Black Soldier Fly (Hermetia illucens), enables the efficient bioconversion of organic waste into high-quality protein, thereby diverting waste from landfills and reducing methane emissions a particularly potent GHG (Rehman et al., 2023). Moreover, insect cultivation typically requires far less land and water than conventional crop-based protein sources (van Huis et al., 2013). Similarly, the

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valorisation of food waste into protein serves the dual purpose of lowering emissions from waste disposal while generating a valuable feed resource.

The adoption of these alternative proteins in Sub-Saharan Africa's livestock systems is aligned with broader global objectives to decarbonize agricultural value chains and promote a circular bioeconomy (Chia et al., 2019). Continued investment in scalable production models and supportive policy frameworks will be essential to realize their full environmental and economic potential in the region.

In the same vein, land degradation and deforestation, which are often driven by the expansion of agricultural land for feed and food production, constitute pressing environmental concerns across Sub-Saharan Africa (Smetana et al., 2016). Hence, reducing the land footprint of livestock feed production emerges as a critical criterion for evaluating the sustainability of alternative protein sources. This study indicated that microalgae and Black Soldier Fly (BSF) larvae production systems exhibit remarkable land-use efficiency. According to van Huis et al. (2013), these systems require approximately 60–80% less land per kilogram of protein produced compared to conventional protein sources such as soybean meal. Also, microalgae species, including Spirulina platensis and Chlorella vulgaris, can be cultivated in bioreactors or open pond systems located on non-arable land, such as saline or arid zones, thereby avoiding direct competition with food crops for fertile land (García-Encinas et al., 2025). This cultivation strategy not only alleviates land pressure but also opens opportunities for ecological restoration and reallocation of prime agricultural land to more critical food production or conservation uses. Similarly, BSF larvae production systems are characterized by a compact, vertical design, enabling their deployment in urban and peri-urban settings. This spatial efficiency significantly reduces the need for arable land and supports decentralized protein production models (De Vivo et al., 2021). Therefore, in SSA, where land scarcity, degradation, and competition for agricultural space are escalating, efficient land-use practices offer a viable pathway for expanding livestock production without exacerbating environmental degradation or contributing to agricultural encroachment.

Regarding the cost efficiency, the economic feasibility of alternative protein sources is a critical factor influencing their adoption, particularly among smallholder farmers in Sub-Saharan Africa (SSA), where affordability directly affects feed accessibility and, by extension, livestock productivity (De Vivo et al., 2021). The results from the meta-analysis indicated that agro-waste-based feed ingredients can be 50–80% less expensive than commercial protein concentrates, despite their relatively lower Crude Protein (CP) content. This agrees with the suggestions of Su et al. (2025), who advocate for a reduction in the cost of production of livestock feeds using alternative protein sources, especially in SSA's agricultural systems.

Regional Disparities and Knowledge Gaps

The rising demand for livestock products in Sub-Saharan Africa (SSA) underscores the urgent need for a resilient and sustainable feed supply. While preceding sections have examined the nutritional profiles and sustainability attributes of alternative protein sources, an equally important dimension involves understanding the geographical distribution of research activities across the region.

This systematic review and meta-analysis not only consolidate existing evidence on alternative protein feedstuffs but also identify spatial patterns in research efforts. By mapping the geographical spread of eligible studies, this work reveals regional disparities, highlights established research hubs, and uncovers areas that remain underexplored. A notable disparity was observed in the geographic distribution of research, as shown in Figure 2. Most studies originated from Nigeria, Kenya, and Uganda, while several SSA countries (e.g., Angola, Chad, Sierra Leone) had no published trials despite facing acute feed protein deficits. Moreover, most studies focused on poultry and pigs, with relatively few on cattle, goats, or sheep, which are more important in arid regions. In addition, few studies provided longitudinal data or full cost–benefit analysis, and only 25% included environmental impact assessments. This spatial analysis, therefore, offers critical insights into national and sub-regional research priorities, guiding future scientific inquiry and policy interventions. It also serves as a foundation for directing targeted investment toward underrepresented areas, thereby fostering a more equitable and comprehensive development of alternative protein feed systems in SSA. The results of this study should also encourage policymakers and researchers to invest in new studies in underrepresented areas, instead of only focusing on regions that already have a lot of research.

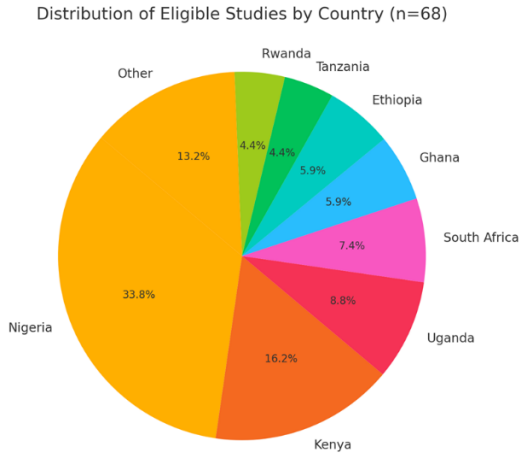

Fig. 2: Pie chart showing the distribution of 68 eligible studies across 17 Sub-Saharan African countries

Nevertheless, the results of this study could imply that a substantial share of the studies appears to be concentrated in a few countries with stronger research infrastructure and funding, notably Nigeria and Kenya. This concentration provides robust and well-supported insights for these nations, but limits the direct applicability of the findings to many other Sub-Saharan African countries. The efficiency and sustainability of alternative protein sources, such as black soldier fly meal and Spirulina, are shaped by local conditions—including climate, feed resource availability, market dynamics, and cultural practices. Consequently, the meta-analysis provides strong evidence for regions with extensive data, while serving as a valuable basis for hypothesis generation in countries with limited or no representation in the existing literature.

Implications for Livestock Policy and Practice

This review supports the incorporation of alternative protein sources into national feed strategies, especially in countries that import a lot of conventional protein sources for livestock production. Policies promoting insect farming, legume intercropping, and agro-waste valorisation could reduce feed costs, reduce competition for conventional protein sources between human beings and animals, improve food system resilience, and generate local employment. The development of quality assurance frameworks, processing guidelines, and training programs will be essential to ensure the safety and acceptability of these alternative proteins.

Conclusion

This systematic review and meta-analysis confirm that alternative protein sources, particularly insect meals, legume-based feeds, agro-industrial byproducts, and algae, offer viable pathways to improve the efficiency and sustainability of livestock production in sub-Saharan Africa. Among these, black soldier fly larvae demonstrated the highest nutritional efficiency and environmental sustainability, while legumes and oilseed byproducts provided moderate performance with strong regional availability. Despite this promise, research remains unevenly distributed across the region and species, and there are limited lifecycle assessments and cost analyses. Scaling these solutions will require region-specific trials, improved processing technologies, enabling policies that promote innovation and safety in alternative protein systems, and a more conducive policy and regulatory environment.

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Authors Contributions

Olusegun Ikusika: Conceptualization: Methodology, Supervision, Writing - original draft preparation, Writing - review and editing, Funding acquisition.
Luvuyo Bulo: Formal analysis and investigation.
Bulo Luvuyo: Writing - review and editing.
Jaja Ishmeal Festus: Supervision.

Ethics

This is a review article; it does not need an ethical certificate. However, protocol regarding systematic review was adhered to.

Declaration of Conflict of Interest

The authors have no competing interests to declare that are relevant to the content of this article.

Data Availability

Data will be made available at reasonable requests from the corresponding author.

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