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REVIEW ARTICLE

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Forage-based livestock systems, insectivorous birds, and veterinary ecology: integrative review

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Abstract

Veterinary sciences are increasingly central to the development of sustainable forage-based livestock systems, as they integrate animal health, nutrition, ecosystem functioning, and climate resilience within a One Health framework. This integrative review synthesizes current evidence on the evolving role of veterinary science in complex livestock agroecosystems, with particular emphasis on forage diversity, insect-mediated trophic processes, and the ecological functions of aerial insectivorous birds. The review highlights limitations of conventional livestock nutrition approaches that prioritize cost minimization and overlook ecological variability, seasonal dynamics, and non-livestock fauna. Forage-based systems, especially in tropical regions, benefit from diversified plant communities that enhance insect abundance, nutrient cycling, and ecosystem services, indirectly supporting livestock productivity and health. Swiftlets and swallows are examined as key ecological actors that regulate insect populations, contribute to nutrient redistribution, and interact closely with livestock-dominated landscapes. Climate change emerges as a major driver affecting forage quality, feed efficiency, and system stability, necessitating adaptive strategies such as precision feeding, climate-smart livestock systems, silvopastoral integration, and genetic adaptation. Despite growing interdisciplinary evidence, gaps remain in integrating avian ecology, insect-derived nutrient flows, and veterinary nutrition into coherent management frameworks. Addressing these gaps through interdisciplinary, data-driven, and translational research is essential to enhance the resilience, productivity, and sustainability of forage-based livestock agroecosystems

KEYWORDS
veterinary ecology, forage-based livestock systems, insectivorous birds, climate-smart livestock systems.

1. INTRODUCTION

Veterinary sciences are increasingly recognized for their role in improving the sustainability and resilience of forage-based livestock systems by integrating animal health, nutrition, and ecosystem processes (Pathak & Kim, 2022, 2024, 2025; Butt & Ahmed, 2025; Kumar et al., 2025; Shaikh et al., 2025). However, conventional livestock approaches remain largely focused on productivity and cost efficiency, often overlooking ecological interactions that influence nutrient dynamics, pest regulation, and animal health outcomes (Usigbe et al., 2025).

Forage-based livestock systems are particularly vulnerable to climate variability, as fluctuations in temperature, rainfall, and extreme events directly affect forage availability, quality, and seasonal stability. These changes influence not only animal nutrition but also insect populations and trophic interactions within agroecosystems. Consequently, improving system resilience requires a broader ecological perspective that integrates forage diversity, trophic connectivity, and ecosystem services.

Although previous studies have explored forage systems, livestock nutrition, and agroecology, they have generally treated these components separately. Limited attention has been given to the integration of insect-mediated nutrient pathways and the ecological roles of aerial insectivorous birds within livestock production systems. In particular, the contribution of insects as nutrient intermediaries and the role of birds such as swiftlets (Aerodramus spp.) and swallows (Hirundo rustica) in regulating insect populations remain underexplored in veterinary science.

Limited attention has been given to the integration of insect-mediated nutrient pathways and the ecological roles of aerial insectivorous birds within livestock production systems.

In forage-based systems, plant diversity supports insect abundance and diversity, which in turn facilitates trophic connectivity and nutrient cycling (Yang & Chen, 2021; Bainard et al., 2020). These insects function as key intermediaries linking forage resources to higher trophic levels. Aerial insectivorous birds exploit these insect populations and provide ecosystem services such as pest regulation, which can improve forage quality and reduce livestock exposure to harmful insects.

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From a veterinary perspective, these interactions are highly relevant. Non-livestock fauna—including insects and insectivorous birds—contribute directly to livestock health and productivity by influencing feed quality, reducing pest pressure, and lowering disease risks. This expands the scope of veterinary science beyond conventional boundaries toward a more integrative, ecosystem-based approach aligned with One Health principles.

Therefore, this review aims to address a critical gap by integrating forage diversity, insect-derived nutrient dynamics, and avian ecological functions within a veterinary science framework. The novelty of this manuscript lies in connecting these components into a unified conceptual model that links ecosystem processes with livestock productivity, health, and climate resilience.

2. CHARACTERISTICS OF FORAGE-BASED LIVESTOCK PRODUCTION SYSTEMS

Forage-based livestock production systems are characterized by their reliance on diverse forage species, which offer lower production costs and adaptability across various climates and soil types (Severino da Silva, 2025). These systems are complex and require a comprehensive approach to enhance resilience, considering the specific conditions, needs, goals, and resources of each system. Key attributes include: Forage Diversity and Nutrient Management: Incorporating a variety of forage species can extend grazing seasons and improve nutrient availability, which is crucial for sustainable production (Severino da Silva, 2025); Animal Traits: Livestock in these systems must exhibit traits such as feed efficiency, reproductive fitness, health, and adaptability to fluctuating feed supplies (Delaby et al., 2021; Washburn & Mullen, 2014); Economic Efficiency: Systems that extensively use fresh grass can achieve high economic efficiency by reducing costs associated with concentrates, buildings, and labor (Gazzarin et al., 2018).

In tropical regions, various forage-based systems are employed, including grazing, cut-and-carry, and mixed crop-livestock systems (MCLS): Grazing Systems: These systems are influenced by climate, soil, and forage resources, and include pastureland, cropland, forestland, and rangeland (Fynn et al., 2017). Grazing management is crucial for optimizing forage intake and animal performance, with systems like rotational stocking enhancing productivity (Barsotti et al., 2024; Pezzopane et al., 2020); Cut-and-Carry Systems: These involve harvesting forage and transporting it to livestock. For example, the APSIM-Tropical Pasture model has been used to simulate the productivity of tropical pastures under cut-and-carry management, showing high accuracy in predicting forage growth (Bosi et al., 2020); Mixed Crop-Livestock Systems (MCLS): These systems integrate crops and livestock to enhance sustainability and productivity. In tropical regions, MCLS can improve soil carbon sequestration and nutrient cycling, contributing to better soil health and higher crop yields (Marchão et al., 2024; Sierra et al., 2025). For instance, integrating trees with pastures (ICLF systems) can improve animal welfare and offset greenhouse gas emissions, although it may reduce forage yield due to competition for resources (Carneiro et al., 2025; Sarto et al., 2020).

Effective integration of crops, livestock, and forestry can lead to sustainable agricultural development, with benefits such as improved soil health, nutrient cycling, and reduced environmental impact (Carneiro et al., 2025; Marchão et al., 2024). Livestock performance in these systems depends on the balance between forage availability and quality, and the ability to manage environmental and seasonal variations (Barsotti et al., 2024; Ortega-Jimenez et al., 2006). Forage-based systems can be economically viable and environmentally sustainable by optimizing forage use, reducing reliance on external inputs, and enhancing ecosystem services (Marchão et al., 2024; Sierra et al., 2025). In summary, forage-based livestock production systems in tropical regions are diverse and complex, requiring tailored management practices to optimize productivity and sustainability. These systems benefit from integrating various forage species, managing grazing and cut-and-carry practices, and incorporating mixed crop-livestock approaches to enhance resilience and efficiency.

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3. FORAGE DIVERSITY, INSECT ABUNDANCE, AND TROPHIC CONNECTIVITY

Increasing plant species diversity generally enhances insect diversity. Diverse plant communities provide more niches and food resources, supporting a greater variety of insects (Yang & Chen, 2021; Zhu et al., 2008). Plant functional composition also plays a crucial role. For example, legume communities tend to have higher shoot biomass but lower insect herbivory and grasshopper performance compared to other plant types (Nitschke et al., 2015). In grassland ecosystems, the functional composition of insect herbivores (e.g. grass-feeders vs. mixed-feeders) significantly affects plant biomass, with grass-feeders reducing plant biomass more than mixed-feeders (Laws et al., 2018). Agricultural intensification, such as increased cutting frequency and fertilizer application, can reduce plant diversity, which in turn negatively impacts insect diversity and abundance (Everwand et al., 2014). Field margins with diverse forage species can serve as refuges for pollinators, enhancing forage species richness and supporting insect diversity (Denisow & Wrzesień, 2015). Insect herbivory can influence nutrient cycling in ecosystems. For instance, herbivory increases nutrient concentrations in throughfall, which is further affected by plant diversity (Nitschke et al., 2015). The presence of diverse plant species can lead to better nutrient profiles in forage, which indirectly supports higher insect diversity (Bainard et al., 2020).

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Trophic cascades, where predators indirectly affect plant biomass by controlling herbivore populations, are a key mechanism in plant-insect interactions. These cascades can be influenced by the complexity and diversity of the food web (Corcket et al., 2017). In grassland ecosystems, the functional composition of insect herbivores can drive these trophic cascades, affecting plant community structure and biomass (Laws et al., 2018). The nutritional quality of primary producers significantly influences the trophic structure of ecosystems. Higher nutritional quality leads to more efficient trophic transfer, supporting higher consumer productivity and faster energy recycling (Cebrian et al., 2009). In aquatic ecosystems, nutrient enrichment can shift the trophic position of omnivores towards herbivory, altering food web dynamics (van der Lee et al., 2021). Different primary producers (e.g. seagrass, macroalgae) contribute variably to the diets of consumers in marine ecosystems. For instance, seagrass detritus supports many fish species, while macroalgae and epiphytes are crucial for invertebrates (Belicka et al., 2012; Kieckbusch et al., 2004). In terrestrial ecosystems, plant diversity can enhance predator and parasitoid abundance, which in turn reduces herbivore abundance and damage, promoting overall plant performance (Wan et al., 2020).

Table 1. Interactions between plant diversity, functional traits, and trophic dynamics in ecosystem functioning

Aspect	Key Findings	References
Plant Diversity	Enhances insect diversity by providing more niches and food resources	(Yang & Chen, 2021; Zhu et al., 2008)
Functional Composition	Affects plant biomass and insect herbivory; legumes show higher biomass but lower herbivory	(Laws et al., 2018; Nitschke et al., 2015)
Agricultural Practices	Intensification reduces plant and insect diversity; diverse field margins support pollinators	(Denisow & Wrzesień, 2015; Everwand et al., 2014)
Nutrient Cycling	Herbivory influences nutrient concentrations; diverse plants improve nutrient profiles	(Bainard et al., 2020; Nitschke et al., 2015)
Trophic Cascades	Predators control herbivores, affecting plant biomass; driven by food web complexity	(Corcket et al., 2017; Laws et al., 2018)
Nutritional Quality	Higher quality leads to efficient trophic transfer and higher consumer productivity	(Cebrian et al., 2009; van der Lee et al., 2021)
Primary Producers	Variable contributions to consumer diets; seagrass and macroalgae are significant	(Belicka et al., 2012; Kieckbusch et al., 2004)

This synthesis highlights the intricate relationships between forage diversity, insect abundance, and trophic connectivity, emphasizing the importance of plant diversity and functional composition in shaping these dynamics.

4. SPECIES DISTRIBUTION AND HABITAT UTILIZATION IN AGRICULTURAL ENVIRONMENTS

Swiftlets (*Aerodramus spp.*) have shown adaptability to various landscapes, including urban, mixed-use, and monocrop areas. They are opportunistic feeders, with their diet reflecting the availability of insect prey within their foraging ranges (Arazmi et al., 2025b; Chan et al., 2019). Swiftlets commute between their colonies and primary feeding grounds, which can be more than 30 km apart, indicating their reliance on natural forests for high insect availability (Fujita & Leh, 2019). Swallows (*Collocalia spp.* and *Hirundo spp.*) particularly barn swallows (Hirundo rustica), are closely associated with livestock farming. The presence of livestock and manure heaps significantly increases food availability, enhancing reproductive success and nestling survival (Grüebler et al., 2010; Luhr & Groschel, 2006). Barn swallows are also found to forage more in areas with mixed field types and tall trees, which help concentrate prey (Henderson et al., 2007).

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Swiftlets adapt their feeding behavior based on the availability of insects in different landscapes. They primarily feed in natural forests but also utilize suburban and rural landscapes as secondary feeding areas (Fujita & Leh, 2019). Their diet includes a variety of arthropods, with significant consumption of agricultural pests, highlighting their role in natural pest management (Arazmi et al., 2025b; Chan et al., 2019). Barn swallows benefit from the microhabitat provided by livestock farms, such as stable temperatures and increased insect availability around manure heaps (Luhr & Groschel, 2006). This association is crucial for their reproductive success, particularly for double-brood pairs (Grüebler et al., 2010). Swallows exhibit higher foraging activity in areas with livestock and mixed field types. The presence of tall trees in boundaries is also significant, especially in arable regions (Henderson et al., 2007)

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Table 2. Habitat use, diet, and behavioral adaptations of aerial insectivorous birds in modified landscapes

Species	Primary Habitat	Secondary Habitat	Diet	Behavioral Adaptation
Swiftlets	Natural forests	Urban, mixed-use, monocrop	Diverse arthropods, agricultural pests	Long-distance commuting, opportunistic feeding
Barn Swallows	Livestock farms	Mixed field types, tall trees	Insects around livestock, manure heaps	Nesting in stables, foraging in mixed landscapes

Swiftlets and swallows exhibit significant adaptability to livestock-dominated landscapes. Swiftlets rely on natural forests for primary feeding but can utilize modified landscapes opportunistically. Barn swallows benefit from the microhabitat and food availability provided by livestock farming, which enhances their reproductive success and foraging efficiency. Conservation efforts should focus on maintaining habitat heterogeneity and supporting livestock farming practices that benefit these aerial insectivores. The adaptability of swiftlets and swallows to agricultural and livestock-dominated landscapes has direct implications for animal production systems. Their ability to exploit habitats such as pastures, farms, and mixed-use landscapes allows them to access insect populations associated with livestock activities. This enhances their role in biological pest control, contributing to improved forage quality, reduced insect pressure, and better livestock health. From a veterinary perspective, this adaptability supports preventive health management and ecosystem-based livestock production.

5. FLIGHT-BASED FORAGING BEHAVIOR AND LANDSCAPE USE

In terrestrial agroecosystems, flight-based foraging behavior of aerial insectivorous birds plays a critical role in linking landscape structure with insect population dynamics. Species such as swiftlets and swallows actively forage over pastures, crop fields, and livestock facilities, where insect abundance is influenced by forage diversity and organic inputs. Unlike seabird-based systems, these interactions occur directly within livestock production landscapes, making them more relevant to agricultural contexts. This behavior supports insect regulation, enhances ecosystem stability, and contributes to maintaining forage quality in grazing systems. Cape gannets exhibit sex-specific temporal foraging behaviors, with females more likely to forage in the morning and midday, while males increase foraging activity in the late afternoon (Botha et al., 2017). Common terns show peaks of foraging activity after sunrise and before sunset, likely in response to prey availability and to prepare for nocturnal fasting (Militão et al., 2023). Brown pelicans adjust their foraging habitat quality over the breeding season, initially foraging in suboptimal habitats and later optimizing their foraging patch use as energetic needs increase (Geary et al., 2020). Shelducks exhibit exploratory movements before the flightless molting period, indicating a need to adapt to small-scale habitat changes (Cimiotti et al., 2024). Masked boobies forage at nested hierarchical scales, influenced by mesoscale oceanographic features such as sea surface height anomaly and water velocity (Poli et al., 2017). Balearic shearwaters primarily forage on the Iberian continental shelf but can extend their range to the North African shelf under favorable wind conditions (Afán et al., 2021). Australasian gannets show high interannual variability in foraging distances and trip durations, with core foraging areas differing between sexes (Besel et al., 2018). Red knots exhibit different space-use patterns based on resource distribution, with high aggregation and low site fidelity in resource-rich areas, and solitary, site-faithful behavior in areas with smaller resource patches (Oudman et al., 2018).

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Woodland birds provide pest control in crop fields adjacent to woody edges, with most foraging activity occurring within 20 meters of the edge (Puckett et al., 2009). This suggests a significant overlap between avian foraging zones and agricultural areas, enhancing pest control services. In alfalfa fields, complex edge habitats with trees increase bird abundance and diversity, leading to reduced pest insect populations near the field edge (Kross et al., 2016). Foraging seabirds like the

Balearic shearwaters and Masked boobies utilize productive coastal and shelf-slope fronts, indicating an overlap with areas of high marine productivity (Afán et al., 2021; Poli et al., 2017). Common terns forage in shallow coastal waters up to 20 km from their colony, often outside protected areas, highlighting the need for conservation strategies that consider these foraging zones (Militão et al., 2023).

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6. NUTRITIONAL COMPOSITION OF INSECTS IN FORAGE ECOSYSTEMS

Insects are recognized for their high nutritional value, making them a viable alternative protein source. The protein content in insects ranges from 35% to 61%, with some species like termites and locusts reaching the higher end of this spectrum (Priya & Kumar, 2023). Lipid content varies significantly, from 13% to 39.5%, with palm weevils having the highest fat content (Ojha et al., 2021). Insects also provide essential fatty acids, including linoleic and linolenic acids, which are crucial for human health (Kinyuru et al., 2015). In addition to macronutrients, insects are rich in micronutrients such as iron, zinc, magnesium, and copper, with levels comparable to recommended daily intakes (Awobusuyi et al., 2021). They also contain vitamins, particularly from the B group, and other essential nutrients like chitin, which serves as dietary fiber (Kinyuru et al., 2015; Ojha et al., 2021). The energy content of insects is substantial, making them a dense source of nutrition (Zhou et al., 2022). The nutritional value of insects is significantly influenced by their diet, which includes the quality of forage they consume. Forage quality, determined by factors such as protein, mineral content, and digestible energy, directly impacts the nutritional composition of insects (Hoveland & Monson, 1980; Wróbel et al., 2025). For instance, insects fed on high-quality forage with optimal protein and mineral content tend to have higher nutritional value (Espitia Buitrago et al., 2021; Pinotti & Ottoboni, 2021).

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Environmental conditions and forage management practices also play a crucial role. Factors such as soil fertility, grazing systems, and conservation methods (e.g. haymaking and silage production) can enhance forage quality, thereby improving the nutritional profile of insects that feed on these forages (Wróbel et al., 2025). Additionally, the stage of maturity of the forage affects its digestibility and protein content, which in turn influences the nutritional value of the insects (Hoveland & Monson, 1980). Insects' ability to convert various substrates, including low-quality organic material, into high-quality biomass is notable. This bioconversion process is influenced by the nutrients present in the substrate, such as fats, carbohydrates, and fiber, which define the features of the insect biomass (Pinotti & Ottoboni, 2021). Overall, optimizing forage quality through integrated agronomic practices and sustainable management strategies is essential for enhancing the nutritional value of forage-associated insects (Espitia Buitrago et al., 2021; Wróbel et al., 2025). Future research should focus on developing resilient forage systems that maintain high nutritional value while adapting to changing climatic conditions.

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Table 3. Nutrient composition and factors influencing the nutritional content of insects as feed resources

Nutrient	Range/Content	Influencing Factors
Protein	35% - 61%	Species, diet, developmental stage, forage quality (Awobusuyi et al., 2021; Ojha et al., 2021; Priya & Kumar, 2023)
Lipids	13% - 39.5%	Species, diet, forage quality (Awobusuyi et al., 2021; Ojha et al., 2021)
Micronutrients	Iron, zinc, magnesium, copper, B vitamins	Species, diet, forage quality (Awobusuyi et al., 2021; Kinyuru et al., 2015; Zhou et al., 2022)
Energy	High energy content	Species, diet, forage quality (Ojha et al., 2021; Zhou et al., 2022)
Fiber (Chitin)	3.2% - 5.2%	Species, diet (Awobusuyi et al., 2021; Ojha et al., 2021)

By understanding and managing these factors, the nutritional value of forage-associated insects can be optimized, contributing to sustainable food systems and improved nutritional outcomes.

7. NUTRITIONAL ECOLOGY OF SWIFTLETS AND SWALLOWS

Both swiftlets and swallows primarily feed on flying insects, but there are notable differences in their dietary preferences and feeding efficiency. For instance, Barn Swallows and house-farmed swiftlets in Peninsular Malaysia show only about a 10% dietary overlap at lower taxonomic levels, indicating distinct dietary niches despite both consuming a high proportion of hymenopterans (Mansor et al., 2020). Similarly, House Martins, Barn Swallows, and Swifts in Poland exhibit significant differences in diet composition, with House Martins having the most diverse diet, followed by Swallows, and then Swifts (Orłowski & Karg, 2013). The foraging efficiency of these birds is influenced by their morphological adaptations. Swallows, for example, have deeply forked tails which may have evolved due to sexual selection or foraging efficiency. However, there is an evolutionary tradeoff between tail morphology and reproductive investment, as seen in both swallows and swifts (Hasegawa & Arai, 2018). Additionally, Tree Swallows' reproductive timing is influenced by food abundance and weather, with greater insect abundance leading to earlier laying and heavier eggs (Nooker et al., 2005).

Similarly, House Martins, Barn Swallows, and Swifts in Poland exhibit significant differences in diet composition, with House Martins having the most diverse diet, followed by Swallows, and then Swifts.

The nutritional intake of these birds has direct implications for their health and reproductive success. For instance, the nutritional value of edible bird nests (EBNs) produced by swiftlets includes essential proteins, amino acids, and other compounds beneficial for tissue repair, immune regulation, and overall health (Arya et al., 2025; Fan et al., 2022). This high nutritional value supports the health and reproductive success of swiftlets, which in turn affects their population dynamics. The availability of food resources and environmental conditions significantly impact the population dynamics of these birds. For example, a decline in insect populations due to habitat degradation can affect the production of EBNs and the sustainability of swiftlet populations (Abdullah et al., 2025). Similarly, sudden weather changes can lead to starvation and mortality in swallows, as observed in a case where a cyclone caused a sudden drop in temperature and insect availability, leading to the death of several swallows (János et al., 2025). The reproductive strategies of these birds are closely tied to their nutritional ecology. For instance, Tree Swallows adjust their reproductive timing based on short-term food intake rates, indicating that they are "income" breeders (Nooker et al., 2005). In contrast, Barn Swallows show signs of senescence with reduced reproductive performance and increased parasite loads as they age, which may be influenced by their nutritional status and environmental conditions (Møller et al., 2005).

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Table 4. Comparative aspects of diet, foraging efficiency, nutritional benefits, and population dynamics between swiftlets (*Aerodramus spp*.) and swallows (*Hirundo rustica*)

Aspect	Swiftlets (Aerodramus spp.)	Swallows (Hirundo rustica)
Primary Diet	Flying insects (e.g. Hymenoptera, Diptera)	Flying insects (e.g. Hymenoptera, Diptera)
Dietary Overlap	~10% with Barn Swallows (Mansor et al., 2020)	~10% with house-farmed swiftlets (Mansor et al., 2020)
Feeding Efficiency	Influenced by morphological traits (Hasegawa & Arai, 2018)	Influenced by tail morphology (Hasegawa & Arai, 2018)
Nutritional Benefits	High nutritional value in EBNs (Arya et al., 2025; Fan et al., 2022)	Dependent on insect abundance (Nooker et al., 2005)
Reproductive Impact	Supports health and reproduction (Arya et al., 2025; Fan et al., 2022)	Affected by food abundance and weather (Nooker et al., 2005)
Population Dynamics	Affected by habitat degradation (Abdullah et al., 2025)	Affected by sudden weather changes (János et al., 2025)

In conclusion, the nutritional ecology of swiftlets and swallows is intricately linked to their dietary preferences, feeding efficiency, and environmental conditions, all of which have significant implications for their health, reproduction, and population dynamics.

8. REGULATION OF INSECT POPULATIONS AND ECOSYSTEM BALANCE

Insectivorous birds play a crucial role in controlling insect populations across various ecosystems, including forests, agricultural lands, and urban areas. Their predation on insects provides significant ecosystem services by reducing pest populations and mitigating damage to vegetation and crops. Birds contribute to pest control by preying on herbivorous insects, which helps maintain forest health. Studies have shown that bird predation can significantly reduce caterpillar populations and leaf damage in forests (Bereczki et al., 2015). The presence of diverse and abundant bird communities, supported by heterogeneous forest structures, enhances this pest control service (Bereczki et al., 2014). In agroforestry and agricultural landscapes, birds help control insect pests, thereby supporting crop productivity and reducing the need for chemical pesticides. For example, in cacao plantations, bird exclusion experiments demonstrated increased leaf damage and arthropod abundance, highlighting the importance of birds in pest management (Cassano et al., 2016). Similarly, in vineyards, bird predation on model prey was higher in areas with greater habitat heterogeneity, suggesting that diverse landscapes support more effective pest control by birds (Barbaro et al., 2017). In suburban woodlands, bird predation on canopy-living arthropods was influenced by forest management practices. Dense understory vegetation supported higher bird predation rates compared to cleared understory areas (Heyman & Gunnarsson, 2011).

The regulation of insect populations by birds has direct implications for forage quality and livestock health by reducing pest pressure and improving the quality of grazing lands. Birds help maintain the quality of forage by controlling insect pests that damage pasture plants. For instance, the presence of insectivorous birds in pastures can reduce the abundance of pests like spittlebugs, which are known to cause significant damage to forage grasses (Monteiro et al., 2021). This pest control service ensures healthier and more productive pastures for livestock. By reducing the populations of biting and blood-feeding insects, birds indirectly contribute to livestock health. Insects such as flies and mosquitoes can cause stress, blood loss, and disease transmission in livestock. Effective pest control by birds can mitigate these issues, leading to better livestock performance and reduced economic losses (Boonsaen et al., 2024).

In practical livestock systems, insectivorous birds contribute to the regulation of key pest groups. For example, predation on spittlebugs and grass-feeding insects helps maintain pasture productivity and forage quality. Additionally, consumption of hematophagous insects such as flies and mosquitoes reduces livestock stress, irritation, and potential disease transmission. These effects are particularly important in grazing systems, where insect pressure can directly influence feed intake, weight gain, and animal welfare. By naturally suppressing pest populations, birds also reduce reliance on chemical insecticides, supporting more sustainable and environmentally friendly livestock management practices. From a veterinary perspective, these ecosystem services contribute to preventive health strategies, improving animal welfare and reducing disease risks associated with insect vectors.

9. NUTRIENT CYCLING AND ECOSYSTEM SERVICES

Insectivorous birds play a significant role in nutrient cycling within ecosystems. They contribute to nutrient redistribution primarily through their feeding activities and subsequent excretion. These birds consume a variety of arthropods, which can include both pests and beneficial species, thus influencing the nutrient dynamics in their habitats. For instance, in cider apple orchards, the diet of insectivorous birds was found to include both pest and non-pest arthropods, indicating their role in pest control and nutrient cycling (Jiménez-Albarral et al., 2025). Additionally, insectivorous birds in wetland ecosystems, such as tidal marshes, significantly reduce the populations of concealed-feeding insects, thereby impacting nutrient cycling through their predation activities (Xiong et al., 2010). Bird guano is a critical source of nutrients, particularly nitrogen (N) and phosphorus (P), which can significantly enrich soils and influence ecosystem dynamics. Several studies highlight the impact of guano deposition on nutrient enrichment. Seabirds, such as those in the Arctic and subantarctic regions, deposit large amounts of guano, which enriches the soil with nutrients like nitrogen, potassium, and phosphate, leading to increased soil conductivity and reduced pH values (Pereira et al., 2025; Zwolicki et al., 2013). This nutrient input can transform nutrient-poor soils into more fertile ones, supporting higher primary productivity and altering vegetation dynamics (Pereira et al., 2025; Smyshlyaeva et al., 2021).

In mangrove rookeries, bird guano significantly increases the concentrations of nitrogen and phosphorus in the soil, enhancing the nutrient status and health of mangrove plants and associated ecosystems (Appoo et al., 2024; McFadden et al., 2016). This nutrient enrichment can lead to increased aboveground biomass and changes in soil composition, although it may also accelerate organic matter decomposition and reduce soil stability (L. T. Simpson et al., 2021). In the Florida Everglades, bird guano has been shown to be a major source of phosphorus enrichment in tree island soils, with guano deposition correlating strongly with increased phosphorus concentrations and specific nitrogen isotope signatures (Irick et al., 2015). Seabird guano can also impact coastal and island ecosystems by providing substantial nutrient inputs that support primary production and influence biogeochemical cycles. For example, on the Channel Islands of California, Western Gulls foraging on human refuse deposit significant amounts of guano, which contributes to nutrient enrichment comparable to agricultural fertilizer applications (Guerra et al., 2022). Overall, the deposition of guano by insectivorous and other birds plays a crucial role in nutrient redistribution and localized nutrient enrichment, significantly impacting ecosystem services and dynamics across various habitats.

10. INDIRECT EFFECTS ON LIVESTOCK NUTRITION AND PRODUCTIVITY

Climate change acts as a key driver influencing all components of the integrated system, including forage production, insect population dynamics, and avian ecological functions. Changes in temperature and precipitation patterns affect forage quality and insect abundance, which in turn influence the availability of resources for aerial insectivorous birds and their capacity to regulate pest populations. Integrating these trophic interactions into climate-smart livestock strategies enhances system resilience by improving adaptive capacity, reducing external inputs, and maintaining ecosystem balance under changing environmental conditions. Climate change significantly impacts forage availability and quality, which in turn affects livestock nutrition and productivity. Extreme weather conditions can lead to reduced forage biomass and increased lignification, making it harder for livestock to digest feed 1. This results in lower feed conversion efficiency and higher methane emissions due to undigested feed (Tamboli et al., 2023). Integrated crop-livestock-forestry (ICLF) systems have shown promise in improving feed efficiency by providing better forage quality and reducing exposure to extreme temperatures, which enhances grazing behavior and feed intake (Barsotti et al., 2024). Utilizing drought-resistant forage crops and improving the nutritional quality of forage through agronomical and breeding methods can mitigate the negative impacts of climate change on livestock nutrition (Chand et al., 2022). Precision feeding and the use of nutraceuticals, probiotics, and feed additives can enhance feed efficiency and animal health, contributing to better productivity and sustainability (Kumari et al., 2025).

Livestock systems need to adapt to both acute and chronic climate stressors. Adaptation strategies include enhancing fodder production, scientific feeding, and integrating livestock with agriculture to reduce vulnerability (Ramana, 2022; Sujatha et al., 2008). Genetic adaptation and precision breeding are critical for improving livestock resilience to climate change. These strategies focus on traits that enhance heat tolerance and metabolic flexibility (Manyike et al., 2025; Rauw et al., 2025). Building resilience in livestock systems involves understanding the adaptive capacity of the system and making trade-offs between short-term socioeconomic performance and long-term sustainability (Herrera & Kopainsky, 2023). Long-term resilience can be enhanced by adopting sustainable management practices, such as improving pasture management, integrating crop-livestock systems, and fostering collaborative frameworks involving various stakeholders (Biswas & Das, 2026; Severino da Silva, 2025). Seasonal variations significantly affect livestock performance. For instance, biochemical and hematological parameters in sheep vary with seasons, impacting their health and productivity (Khalil et al., 2022). Managing these seasonal impacts through appropriate nutritional and health interventions is crucial for maintaining long-term productivity and resilience (Lamy et al., 2012).

Table 5. Impacts of climate change on forage-based livestock systems and strategies for system improvement

Aspect	Impact	Strategies for Improvement
Forage Quality	Reduced by climate change, leading to lower feed efficiency	Use drought-resistant crops, improve forage nutritional quality (Chand et al., 2022; Tamboli et al., 2023)
Feed Efficiency	Affected by forage quality and climate stress	Precision feeding, nutraceuticals, probiotics, feed additives (Kumari et al., 2025)
Climate Adaptation	Essential for resilience to acute and chronic stressors	Genetic adaptation, precision breeding, integrated systems (Manyike et al., 2025; Ramana, 2022; Rauw et al., 2025; Sujatha et al., 2008)
Seasonal Variations	Affect biochemical and hematological parameters, impacting productivity	Nutritional and health interventions tailored to seasonal needs (Khalil et al., 2022; Lamy et al., 2012)
System Resilience	Requires trade-offs between short-term and long-term sustainability	Sustainable management practices, collaborative frameworks (Biswas & Das, 2026; Herrera & Kopainsky, 2023; Severino da Silva, 2025)

In conclusion, improving livestock nutrition and productivity in the face of climate change involves enhancing forage quality, adopting precision feeding strategies, and building system resilience through genetic adaptation and sustainable management practices. These measures are crucial for maintaining long-term animal performance and the overall stability of forage-based livestock systems.

11. VETERINARY ECOLOGY, HEALTH SURVEILLANCE, AND BIOSECURITY CONSIDERATIONS

The provided abstracts do not directly address the use of swiftlets and swallows as bioindicators of agroecosystem health. However, the concept of using bioindicators in agroecosystems is discussed in general terms. For instance, the role of various arthropod predators and their potential as bioindicators in Australian cropping systems is reviewed, though it concludes that their current value as bioindicators is minimal due to limited species diversity and biological knowledge (New, 2007). Additionally, the importance of biodiversity in maintaining agroecosystem health and ecosystem services is highlighted, suggesting that diverse biological communities can be indicative of healthy agroecosystems (Fusaro et al., 2018; Rosas-Ramos et al., 2019). The wildlife-livestock interface is a critical area of concern for veterinary health due to the potential for disease transmission between wild and domestic animals.

Wildlife can act as reservoirs for various diseases that affect livestock. Notable diseases include bovine tuberculosis, brucellosis, avian influenza, and rabies, which have significant implications for livestock health and are challenging to eradicate due to wildlife reservoirs (Miller et al., 2013; Siembieda et al., 2011; Smith et al., 2022). Effective management of diseases at this interface often involves creating Disease Control Areas with buffer zones to contain and manage outbreaks. Strategies may include culling, vaccination, and other control measures tailored to the specific disease and wildlife involved (Hayes et al., 2023; Smith et al., 2022). Diseases at the wildlife-livestock interface can lead to substantial economic losses in animal production and pose public health risks due to zoonotic potential. Over 20% of global animal production losses are attributed to animal diseases, highlighting the economic significance (Karmacharya et al., 2024). A multidisciplinary approach involving veterinary, public health, and environmental professionals is essential for managing these diseases. This approach emphasizes the interconnected health of humans, animals, and the environment (Anderson et al., 2023; Kumar et al., 2025). In regions like Africa, where pastoral and nomadic systems are prevalent, conventional disease control measures are often impractical. These systems are sustainable but face challenges in accessing lucrative export markets due to phyto-sanitary trade rules (Kock, 2004).

12. INTEGRATING SWIFTLET–SWALLOW ECOLOGY INTO VETERINARY NUTRITION AND ANIMAL SCIENCE

Forage-based livestock operations are complex systems influenced by climate, soil types, and production systems. Increasing the resilience of these systems requires a comprehensive approach to assess and understand their conditions, needs, goals, and resources (Severino da Silva, 2025). Insects and Birds: Avian insectivores, such as swifts and swallows, play a crucial role in controlling insect populations, which can benefit livestock by reducing pest-related stress and disease transmission (Arazmi et al., 2025a; Wang et al., 2025). The dietary preferences of these birds, which include a variety of insects, highlight their role in natural pest regulation (Arazmi et al., 2025a). Integration into Veterinary Ecological Thinking: Positioning avian insectivores within veterinary ecological thinking involves recognizing their role in ecosystem energy flow and pest control. This can enhance livestock health and productivity by reducing the need for chemical pest control methods (Arazmi et al., 2025a; Wang et al., 2025).

Climate-Smart livestock systems (CSLS), these systems aim to maintain livestock productivity while reducing greenhouse gas emissions and promoting locally adapted animal genetic resources. Strategies include improving fodder quality, utilizing adapted animal breeds, and integrating indigenous knowledge with scientific practices (Assan, 2026; Manyike et al., 2025). Silvopastoral systems (SPS), these systems combine forestry and grazing, offering benefits such as improved soil water retention, temperature regulation, and enhanced forage production. SPS can make livestock systems more productive, profitable, and resilient to climate change (Cach-Pérez et al., 2021; Dieguez Cameroni et al., 2024). Precision livestock farming, utilizing technologies like remote sensing and deep learning can optimize resource use and improve livestock management. These technologies help predict forage yield and nutrition, manage grazing pressure, and enhance overall system efficiency (Ashworth et al., 2024). Sustainable practices, integrating insect farming into livestock systems can enhance sustainability by promoting nutrient cycling and waste reduction. This approach can improve food security and economic viability while reducing environmental impact (Sokame et al., 2024).

13. KNOWLEDGE GAPS AND FUTURE RESEARCH DIRECTIONS

There is a recognized gap between avian ecology and its integration into veterinary and animal science research. Translational ecology, which involves collaborative efforts between science producers and users from multiple disciplines, has been suggested as a way to bridge this gap. This approach can improve conservation decision-making and ensure that research is relevant to management needs (Saunders et al., 2021). Additionally, the lack of comprehensive data on avian breeding biology, particularly in tropical regions, highlights the need for more focused research efforts in these areas to better understand avian life histories (Xiao et al., 2017). The uneven distribution of research efforts across different species and regions further emphasizes the need for targeted studies to address these disparities (De Lima et al., 2011). Insect-derived nutrient flows in forage systems represent a promising area for future research. Current studies have shown that insects and their symbiotic bacteria play a crucial role in nutrient cycling, particularly in nitrogen fixation and nutrient exchange (Douglas, 2014; Wedin & Russelle, 2020). However, there is a need for standardized methodologies to evaluate the nutritional value and integration of insect-derived products into animal feed systems. This includes refining protein quantification techniques and addressing the unique challenges associated with different forms of insect-derived products (Oddon et al., 2025).

Additionally, the potential of insects like black soldier fly larvae for manure valorization and nutrient recycling in livestock production systems warrants further investigation to optimize large-scale applications (Grassauer et al., 2023). Interdisciplinary approaches in veterinary studies offer significant opportunities for advancing research and education. For instance, interdisciplinary lectures and blended learning formats have been shown to enhance student engagement and learning outcomes in veterinary education (Duckwitz et al., 2021). Collaborative research between human and veterinary medicine, particularly in areas like end-of-life decision-making and comparative pathology, can provide valuable insights and improve both human and animal health outcomes (Groll et al., 2024; Selter et al., 2023). Moreover, the integration of systems biology and bioinformatics in veterinary research can bridge the phenotype-genotype gap and support the development of new vaccines and treatments (Pathak & Kim, 2024). The NIH Comparative Biomedical Scientist Training Program exemplifies how interdisciplinary training can enhance the visibility and impact of veterinary research (R. M.

Simpson et al., 2020). By addressing these knowledge gaps and pursuing the outlined research directions, the integration of avian ecology, the understanding of insect-derived nutrient flows, and the advancement of interdisciplinary veterinary studies can be significantly improved.

14. CONCLUSION

This review highlights the importance of integrating forage diversity, insect-mediated trophic interactions, and the ecological roles of aerial insectivorous birds within a veterinary science framework. Forage diversity supports insect populations that facilitate nutrient cycling and trophic connectivity, while birds such as swiftlets and swallows contribute to pest regulation and ecosystem stability. These interactions have direct implications for livestock systems, including improved forage quality, reduced pest pressure, enhanced animal health, and increased system resilience. Incorporating non-livestock fauna into veterinary science expands the scope of livestock management toward more preventive, ecosystem-based approaches aligned with sustainability and climate adaptation goals. Future research should focus on quantifying these interactions in real production systems and integrating ecological processes into livestock management strategies to support sustainable and climate-resilient agroecosystems.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Rezki Amalyadi was solely responsible for conceptualization, methodology, investigation, data collection, formal analysis, writing—original draft preparation, writing—review and editing, and final approval of the manuscript.

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