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Neuroendocrine-Immune Homeostasis Disruption in Livestock: Molecular Mechanisms, Health Consequences, and Mitigation Strategies A Systematic Literature Review

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Abstract: Livestock are routinely exposed to environmental, nutritional, managerial, and infectious stressors that challenge the neuroendocrine and immune systems. Dysregulation of this integrated axis is increasingly recognised as a principal driver of reduced health resilience and productive performance. This systematic literature review characterised the molecular mechanisms underlying neuroendocrine–immune homeostasis in livestock, identified major disruption categories triggered by stressor exposure, and synthesised evidence-based mitigation strategies. Forty-one peer-reviewed articles from 2020–2026 were retrieved from Scopus, Web of Science, and Google Scholar and analysed through data reduction, display, and conclusion drawing. Findings indicate that chronic HPA axis over-activation triggers six inter-related disturbances: periparturient immunosuppression, Th1/Th2 imbalance, reproductive hormone dysregulation, pro-inflammatory cytokine dysregulation, heat-stress-induced endocrine disruption, and negative energy balance collectively heightening susceptibility to mastitis and metritis while suppressing reproductive efficiency and growth. Effective mitigation requires adaptive housing, precision nutrition, and evidence-based welfare practices to sustain livestock productivity in tropical systems.

Keywords: HPA axis; immune homeostasis; livestock stress; neuroendocrine regulation; periparturient immunosuppression; productivity

Abstrak: *Ternak secara rutin terpapar stressor lingkungan, nutrisi, manajemen, dan infeksius yang menantang sistem neuroendokrin dan imun. Disregulasi aksis terintegrasi ini semakin diakui sebagai faktor utama penurunan ketahanan kesehatan dan performa produktif. Kajian literatur sistematis ini mengkarakterisasi mekanisme molekuler homeostasis neuroendokrin–imun pada ternak, mengidentifikasi kategori gangguan utama akibat paparan stressor, serta mensintesis strategi mitigasi berbasis bukti. Empat puluh satu artikel ilmiah terindeks tahun 2020–2026 ditelusuri dari Scopus, Web of Science, dan Google Scholar, kemudian dianalisis melalui reduksi data, penyajian data, dan penarikan kesimpulan. Temuan menunjukkan bahwa aktivasi berlebihan kronis aksis HPA memicu enam gangguan yang saling berkaitan: imunosupresi periparturient, ketidakseimbangan Th1/Th2, disregulasi hormon reproduksi, disregulasi sitokin pro-inflamasi, gangguan endokrin akibat stres panas, dan keseimbangan energi negatif yang secara kolektif meningkatkan kerentanan terhadap mastitis dan metritis sekaligus menekan efisiensi reproduksi dan pertumbuhan. Mitigasi efektif memerlukan manajemen kandang adaptif, nutrisi presisi, dan praktik kesejahteraan berbasis bukti untuk mempertahankan produktivitas ternak di sistem produksi tropis.*

Kata Kunci: *Sumbu HPA; homeostasis imun; stres ternak; regulasi neuroendokrin; imunosupresi periparturien; produktivitas*

INTRODUCTION

Livestock production represents a cornerstone of global food security, supplying approximately 40% of total agricultural output value and constituting the principal dietary protein source for more than one billion people worldwide (FAO, 2023). Yet the intensification of modern livestock systems has introduced a complex constellation of stressors thermal, nutritional, social, and managerial that persistently challenge the biological equilibrium of production animals (Trevisi & Bertoni, 2009). These stressors are not merely transient perturbations; when sustained, they impose cumulative physiological costs that erode health status, reproductive performance, and productive efficiency at both the individual and herd level (Abecia & Canto, 2026; Alhussien et al., 2024).

Central to the animal's adaptive capacity is the neuroendocrine-immune axis a highly integrated regulatory network in which the nervous, endocrine, and immune systems operate as mutually interdependent subsystems (Chrousos, 2009). The functional core of this axis is the Hypothalamic Pituitary Adrenal (HPA) system, which translates perceived threats into graded hormonal and immune responses through glucocorticoid secretion (Hinds & Sanchez, 2022). Under normal physiological conditions, this response is self-limiting and adaptive; however, chronic or severe stressor exposure overloads the regulatory feedback circuits, producing persistent glucocorticoid excess, immune suppression, and metabolic dysfunction (Ingvartsen & Moyes, 2013).

The clinical significance of this axis is illustrated by mounting experimental evidence. Heat stress, one of the most economically significant environmental stressors in tropical and subtropical livestock systems, has been shown to elevate plasma cortisol concentrations, suppress lymphocyte proliferation, and impair neutrophil function in dairy cattle, small ruminants, and poultry (Alhussien et al., 2024; Tüfekci & Sejian, 2023). Equally, the periparturient period in dairy cattle represents a physiological stress event of particular clinical importance: the simultaneous demands of late-gestation foetal growth, parturition, and early-lactation milk synthesis create a metabolic state of negative energy balance (NEB) that fundamentally compromises the immunocompetence of the transition cow (Drackley, 1999; Sordillo, 2016). Stressors of infectious origin including bacterial endotoxins released during mastitis directly stimulate the HPA axis and drive pro-inflammatory cytokine cascades that, if unresolved, perpetuate chronic immune activation and tissue damage (He et al., 2026; Johnston et al., 2022).

Several reviews have addressed discrete aspects of these phenomena. Johnston et al. (2022) examined the neuroimmune interface in the context of chronic pain in production animals. Alhussien et al. (2024) surveyed heat-stress effects on immunity in livestock. Xie et al. (2025) characterised neuroendocrine-immune regulation of metabolic homeostasis at a molecular level. However, a comprehensive synthesis that integrates the molecular mechanisms of HPA-mediated homeostasis disruption, catalogues the full spectrum of resulting pathological disturbances, and translates that mechanistic understanding into practical evidence-based mitigation strategies remains absent from the literature. This gap is particularly consequential for tropical livestock contexts, where simultaneous exposure to heat stress, nutritional limitation, and high pathogen pressure creates multi-stressor environments that no single-domain review has adequately addressed.

The present systematic literature review addresses this gap. Specifically, it aims to (1) describe the molecular architecture of neuroendocrine-immune homeostasis in livestock, (2) identify and classify the major categories of homeostatic disturbance triggered by environmental, managerial, nutritional, and infectious stressors, (3) document the consequent impacts on health and productive performance, and (4) synthesise current evidence on effective mitigation strategies. By consolidating findings from recent global primary research, this review provides a mechanistic framework to inform livestock management practice and direct future research priorities.

METHODS

Research Design

This study employed a qualitative descriptive literature review based on systematic content analysis (Fadli, 2021). Content analysis was conducted following the conventional approach as described by Hsieh and Shannon (2005), which involves iterative coding of source material without imposing a prior theoretical framework. This design is appropriate when the research objective is to synthesise, classify, and interpret existing knowledge domains rather than to generate primary empirical data. The review protocol was structured to ensure transparency and replicability consistent with best-practice guidelines for systematic reviews in veterinary and biomedical science.

Literature Search Strategy

A structured database search was conducted in March–April 2025 across three electronic databases: SCOPUS, Web of Science, and Google Scholar. Two complementary Boolean search strings were applied: (1) ("neuroendocrine" OR "HPA axis") AND ("immune homeostasis" OR "immune function") AND ("livestock" OR "dairy cattle" OR "poultry" OR "swine"); and (2) ("heat stress" OR "periparturient" OR "negative energy balance") AND ("neuroendocrine" OR "cortisol") AND ("livestock"). Publication years were restricted to 2020–2026 to ensure currency of evidence, with the exception of foundational conceptual papers on HPA axis physiology or transition cow biology, for which a broader temporal range was permissible.

Inclusion and Exclusion Criteria

Articles were included if they (1) were published in peer-reviewed journals indexed in SCOPUS or Web of Science, (2) reported empirical data or synthesised evidence relevant to neuroendocrine-immune regulation in livestock species (cattle, sheep, goats, pigs, and poultry), and (3) addressed at least one of the four review objectives. Articles were excluded if they focused exclusively on laboratory rodent or human models without extrapolation to livestock, if they were conference abstracts without full-text availability, or if the journal showed indicators of predatory publishing (e.g., absence of DOI, unverifiable indexing, or implausibly short peer-review timelines).

Data Extraction and Analysis

From an initial retrieval of 214 records, 41 articles were retained following title–abstract screening (n = 147 excluded) and full-text eligibility assessment (n = 26 excluded for scope mismatch or quality concerns). Data extraction was guided by a structured coding frame encompassing: (1) stressor type and species; (2) mechanism of HPA or neuroendocrine involvement; (3) nature of immune or metabolic disturbance; (4) productive or health outcome; and (5) mitigation strategy examined.

Extracted data were analysed using three sequential stages of content analysis: (1) data reduction selection and classification of relevant information by thematic code; (2) data display systematic organisation of coded information into thematic matrices; and (3) conclusion drawing synthesis of patterns and interpretations across themes (Fadli, 2021). Trustworthiness was enhanced through investigator triangulation: three authors independently coded a 20% random sample of included articles, achieving a Cohen's κ of before consensus discussion, consistent with the "almost perfect agreement" threshold recommended by Lincoln and Guba (1985).

RESULTS AND DISCUSSION

Molecular Architecture of Neuroendocrine-Immune Homeostasis in Livestock

Homeostasis in livestock is maintained through continuous bidirectional communication among the nervous, endocrine, and immune systems three regulatory networks that share a common molecular vocabulary of hormones, neurotransmitters, and cytokines (Xie et al., 2025). This shared signalling language enables rapid, integrated responses to environmental perturbations and constitutes the biological foundation of adaptive health.

The central mediating structure of this regulatory axis is the HPA system. Upon detection of a stressor by sensory neurons, the hypothalamus releases Corticotropin-Releasing Hormone (CRH), which stimulates the anterior pituitary to secrete Adrenocorticotropic Hormone (ACTH). ACTH in turn drives the adrenal cortex to synthesise glucocorticoids principally cortisol in ruminants and corticosterone in poultry (Hinds & Sanchez, 2022). These glucocorticoids exert pleiotropic effects: they promote gluconeogenesis to mobilise energy substrates, suppress pro-inflammatory cytokine synthesis, and inhibit lymphocyte proliferation through both genomic and non-genomic mechanisms (Chrousos, 2009).

Critically, the immune system is not a passive target of neuroendocrine regulation but an active bidirectional partner. Activated immune cells produce pro-inflammatory cytokines interleukin-1β (IL-1β), interleukin-6 (IL-6), and tumour necrosis factor-α (TNF-α) that can penetrate the blood–brain barrier or transmit signals via afferent vagus nerve fibres to directly stimulate hypothalamic CRH neurons, thereby amplifying HPA reactivity (Coverdell et al., 2024). This neuro-immune feedback loop constitutes the mechanistic foundation of homeostasis maintenance, and its dysregulation underlies the pathological states described in subsequent subsections.

At the molecular level, glucocorticoid receptor (GR) signalling is the proximal mechanism through which cortisol exerts immune modulation. GR activation in lymphocytes suppresses nuclear factor-κB (NF-κB) transcriptional activity, thereby reducing the synthesis of adhesion molecules, chemokines, and pro-inflammatory cytokines (Chrousos, 2009; Johnston et al., 2022). Simultaneously, elevated cortisol accelerates lymphocyte apoptosis and redirects immune cell trafficking from peripheral tissues to bone marrow, producing the characteristic lymphopenia observed during acute stress in cattle and pigs (Alhussien et al., 2024). The gut microbiome adds a further regulatory layer: glucocorticoid excess disrupts microbial community composition and disrupts epithelial tight-junction integrity, creating a portal for endotoxin translocation that further amplifies systemic inflammation (Awe et al., 2024; González-Solé et al., 2022; Woś et al., 2025).

Causative Factors of Homeostasis Disruption

Multiple categories of stressor interact to overwhelm the regulatory capacity of the neuroendocrine-immune axis in livestock. These can be organised into four principal domains: environmental, managerial, nutritional, and infectious.

Environmental stressors. Heat stress is the most economically significant environmental stressor globally, particularly severe in tropical regions where ambient temperatures routinely exceed the thermoneutral zone of domestic species. Sustained elevation of core body temperature activates the HPA axis and sympathetic nervous system simultaneously, increasing circulating cortisol and catecholamines while suppressing thyroid hormone concentrations (T3 and T4). These hormonal shifts collectively reduce voluntary feed intake, impair mucosal immunity, and diminish lymphocyte function (Alhussien et al., 2024; Tüfekci & Sejian, 2023). In dairy cattle, heat stress during the dry period has been reported to reduce colostrum immunoglobulin IgG concentrations, thereby compromising passive immunity transfer to the neonate (Tao et al., 2019).

Managerial stressors. High stocking densities, transportation, weaning, and regrouping impose psychosocial stressors mediated through limbic-HPA circuitry. Weaning stress in piglets consistently elevates plasma cortisol, reduces secretory immunoglobulin A (sIgA) in intestinal secretions, and increases intestinal permeability, creating conditions conducive to enteric disease (Tang et al., 2022; Yu et al., 2022). The temporal dynamics of cortisol normalisation following weaning are an important predictor of subsequent growth trajectory and disease susceptibility.

Nutritional stressors. The periparturient period in dairy cattle is characterised by a state of negative energy balance (NEB) as the energy demands of parturition and early lactation outpace dietary intake. NEB drives excessive lipolysis, releasing non-esterified fatty acids (NEFAs) that, at supraphysiological concentrations, directly impair neutrophil and macrophage function (Drackley, 1999; Sordillo, 2016). Deficiencies in specific micronutrients notably zinc (Zn), selenium (Se), and vitamin E further compound immunosuppression by limiting the biosynthesis of antioxidant enzymes and impairing leukocyte oxidative burst capacity (Maulidina et al., 2025).

Infectious stressors. Bacterial pathogens and their endotoxins act as biological stressors that directly engage the HPA axis through pattern-recognition receptor activation in the hypothalamus. This immune-to-brain signalling pathway, mediated by IL-1β and TNF-α, produces "sickness behaviour" characterised by anorexia, lethargy, and fever adaptive responses that divert metabolic resources toward immune defence (Johnston et al., 2022). However, when bacterial challenge is sustained or recurrent, as in subclinical mastitis caused by *Staphylococcus aureus*, chronic HPA activation progressively depletes regulatory capacity and paradoxically impairs the ability to mount effective host defence (He et al., 2026).

Principal Categories of Homeostatic Disruption

When stressor intensity exceeds the regulatory capacity of the neuroendocrine-immune axis, six inter-related categories of homeostatic disruption emerge in livestock (Xie et al., 2025). These disturbances commonly co-occur and interact, creating a cumulative pathophysiological burden.

Periparturient Immunosuppression

The periparturient period spanning approximately three weeks before to three weeks after parturition is characterised by a generalised suppression of innate and adaptive immune function in dairy cows. Declining plasma progesterone, rising oestrogens, concurrent NEB, and the redistribution of inflammatory resources to the uterus collectively compromise circulating neutrophil function and reduce lymphocyte responsiveness to mitogen stimulation (Sordillo, 2016). This creates a critical window of heightened susceptibility to mastitis, retained foetal membranes, metritis, and displaced abomasum that is well-documented in transition dairy herds globally.

Th1/Th2 Balance Disruption

Polarisation of T-helper cell responses toward a Th2 phenotype during the periparturient period driven by progesterone and glucocorticoid excess blunts cell-mediated immunity and impairs the elimination of intracellular pathogens such as mycobacteria and certain viruses. Failure to restore Th1 dominance in the post-partum period predisposes animals to opportunistic infections and prolongs disease resolution, with consequences for both animal welfare and milk production efficiency (Ingvartsen & Moyes, 2013).

Reproductive Hormone Dysregulation

Sustained HPA activation suppresses the hypothalamic-pituitary-gonadal (HPG) axis by reducing GnRH pulse frequency and inhibiting LH surges, leading to anovulation and extended post-partum intervals (Tüfekci & Sejian, 2023). Glucocorticoids additionally exert direct inhibitory effects on ovarian steroidogenesis, reducing oestradiol and progesterone synthesis. These effects manifest clinically as low conception rates, prolonged calving intervals, and impaired embryo survival outcomes that directly reduce the reproductive efficiency and economic returns of beef and dairy operations.

Pro-inflammatory Cytokine Dysregulation

Chronic or repeated stressor exposure dysregulates cytokine production in ways that are simultaneously immunosuppressive and pro-inflammatory. IL-6, produced in excess during NEB and heat stress, drives acute-phase protein synthesis at the expense of albumin and immunoglobulin production. TNF-α impairs insulin signalling, contributing to peripheral insulin resistance and the metabolic syndrome phenotype in high-producing dairy cows (Gu et al., 2023). Uncontrolled cytokine activity also promotes the "sickness behaviour" syndrome anorexia, reduced activity, and social withdrawal that further depresses voluntary feed intake and productive performance.

Endocrine Disruption by Chronic Heat Stress

Sustained heat exposure in poultry and pigs specifically disrupts thyroid axis function, reducing circulating T3 and T4 concentrations. Because thyroid hormones are critical regulators of basal metabolic rate, immune cell proliferation, and intestinal morphology, their reduction has consequences extending well beyond thermoregulation (Rido, 2025). Concurrent cortisol elevation creates an endocrine milieu unfavourable to anabolism, explaining the characteristic reductions in feed conversion efficiency and muscle deposition observed in heat-stressed production animals.

Negative Energy Balance (NEB)

The accumulation of ketone bodies primarily β-hydroxybutyrate (BHBA) during NEB directly impairs leukocyte function by inhibiting oxidative burst activity in neutrophils and reducing lymphocyte proliferation (Drackley, 1999). Concomitant elevations in NEFA and BHBA activate endoplasmic reticulum stress pathways in hepatocytes, impairing the liver's capacity for acute-phase response coordination and further compromising systemic immunity. NEB-associated immune impairment is temporally correlated with the peak incidence of clinical ketosis, hepatic lipidosis, and infectious disease in early-lactation dairy cows a period of critical economic importance for the dairy industry.

Health and Productivity Consequences

The compounding effects of the six disruption categories described above translate into measurable clinical and productive losses across livestock species (Table 1). In dairy cattle, periparturient immunosuppression and NEB synergistically elevate the incidence of mastitis, metritis, retained foetal membranes, and displaced abomasum in the first 30 days post-partum. Mastitis attributable to

Staphylococcus aureus has been linked to HPA-axis-mediated suppression of mammary sIgA production (He et al., 2026). Milk production losses associated with a single clinical mastitis case are estimated at 500–1,000 kg per lactation, with substantially increased culling rates in herds with high disease incidence (Sordillo, 2016).

In pigs, weaning stress generates a consistently documented reduction in average daily gain and feed efficiency during the first two weeks post-weaning, coinciding with peak intestinal permeability and reduced villus height-to-crypt depth ratio (Tang et al., 2022; Yu et al., 2022). In poultry, chronic heat stress reduces egg production, impairs eggshell quality, and reduces breast muscle yield through combined effects of feed intake suppression and oxidative stress-mediated myopathy (Rido, 2025). The consequent escalation in antimicrobial use to manage secondary infections contributes to the global antimicrobial resistance burden, creating regulatory and market-access risks for the industry (Dimuccio et al., 2026).

Table 1. Summary of Homeostatic Disruption Types and Their Health and Productivity Consequences in Livestock

Disruption Type	Species	Health Consequences	Productivity Consequences
Periparturient immunosuppression	Dairy cattle	Mastitis, metritis, retained foetal membranes, ketosis	Reduced milk yield and quality; prolonged days open
Reproductive hormone dysregulation	Dairy and beef cattle	Anoestrus, ovarian cysts, ovulation failure	Reduced conception rate; extended calving interval
Th1/Th2 imbalance	Dairy cattle	Increased susceptibility to intracellular pathogens; opportunistic infections	Reduced production efficiency; elevated treatment costs
Pro-inflammatory cytokine dysregulation	All livestock species	Chronic inflammation, sickness behaviour, anorexia	Reduced average daily gain; impaired feed conversion

Disruption Type	Species	Health Consequences	Productivity Consequences
Chronic heat stress-induced endocrine disruption	Poultry, swine, cattle	Intestinal integrity loss, oxidative stress, immunosuppression	Reduced egg production, carcass quality, growth, and reproductive performance
Negative Energy Balance (NEB)	Dairy cattle	Hepatic lipidosis, hypocalcaemia, subclinical ketosis	Reduced milk production, impaired fertility, increased culling risk

Evidence-Based Mitigation Strategies

Adaptive Environmental Management

Reducing the thermal stressor load through engineering modifications to housing is the most direct and consistently effective mitigation strategy in tropical and subtropical production systems. Installation of shade, forced-air ventilation, and evaporative cooling systems has been shown to reduce peak cortisol concentrations, restore voluntary feed intake, and improve conception rates in dairy cattle under high ambient temperature conditions (Hinds & Sanchez, 2022; Tao et al., 2019). These effects are mechanistically mediated through attenuation of hypothalamic CRH drive, allowing normalisation of HPA axis tone and restoration of immune effector cell function. Monitoring temperature-humidity index (THI) and implementing cooling interventions at THI thresholds above 68 has been recommended as a practical management protocol for dairy operations in Indonesia and comparable tropical environments (Asmarasari et al., 2023).

Precision Nutritional Intervention

Targeted nutritional strategies can modulate the neuroendocrine-immune axis at multiple levels. Energy-dense transition diets formulated to minimise NEFA mobilisation during the early post-partum period reduce the severity and duration of NEB, thereby limiting the immunosuppressive consequences of ketone body accumulation (Drackley, 1999; Sordillo, 2016). Supplementation with trace minerals particularly Zn and Se supports the biosynthesis of superoxide dismutase and glutathione peroxidase, limiting oxidative damage to immune cells during inflammatory episodes (Maulidina et al., 2025).

Phytobiotic compounds have received increasing research attention as neuroendocrine-immune modulators. Curcumin, the principal polyphenolic constituent of turmeric (*Curcuma longa*), has demonstrated dose-dependent effects on antioxidant capacity, pro-inflammatory cytokine suppression, and gut microbiome modulation in heat-stressed broiler chickens (Fathi et al., 2025; Zhang et al., 2024). Fathi et al. (2025) reported significant reductions in plasma TNF-α and IL-6 alongside improved feed conversion in birds supplemented with curcumin nanoparticles. Zhang et al. (2024) corroborated these findings and additionally documented improvements in intestinal morphology and immune cell proliferation. While these results are encouraging, translational application to ruminant species requires further validation, as curcumin bioavailability differs substantially across gastrointestinal morphologies.

Animal Welfare-Based Husbandry

Low-stress handling protocols during transportation, vaccination, and weaning attenuate catecholamine and cortisol surges that would otherwise activate the HPA axis and transiently suppress immune function. The application of stockmanship principles grounded in species-specific ethological knowledge has been shown to reduce handling-induced cortisol peaks and improve post-handling weight gains in cattle (Trevisi & Bertoni, 2009). Prophylactic nutritional support and gradual weaning schedules additionally buffer the magnitude of the stress response in young animals (Tang et al., 2022).

Gut microbiome management through judicious use of probiotics and prebiotics represents an emerging complementary strategy. Selected strains of *Lactobacillus* and *Bifidobacterium* have demonstrated capacity to modulate the gut–brain axis, attenuate HPA reactivity, and enhance sIgA secretion in weaned piglets and calves (Awe et al., 2024; Woś et al., 2025). The mechanistic pathway involves short-chain fatty acid (SCFA) production, particularly butyrate, which reduces intestinal inflammation and enhances epithelial barrier integrity, thereby limiting the endotoxin-mediated amplification of HPA activation described in section 3.1 (González-Solé et al., 2022).

The three strategic domains outlined above are complementary rather than substitutable. Given the multifactorial nature of homeostatic disruption, single-domain interventions consistently produce suboptimal outcomes (Gu et al., 2023). Integrated livestock management programmes that simultaneously address the thermal environment, nutritional status, and handling stress are therefore essential for achieving and sustaining neuroendocrine-immune homeostasis and, consequently, optimal health and productive performance in commercial production systems.

CONCLUSION

Neuroendocrine-immune homeostasis in livestock is maintained through continuous, bidirectional communication among the nervous, endocrine, and immune systems, with the HPA axis serving as the principal integrative hub. Chronic or severe stressor exposure whether environmental, managerial, nutritional, or infectious in origin overloads this regulatory axis and produces six interrelated categories of disturbance: periparturient immunosuppression, Th1/Th2 imbalance, reproductive hormone dysregulation, pro-inflammatory cytokine dysregulation, heatstress induced endocrine disruption, and negative energy balance. These disturbances collectively undermine health resilience and productive efficiency, with major economic consequences for the global livestock industry. Effective mitigation cannot be achieved through single-domain interventions; it requires an integrated approach addressing thermal management, precision nutrition, and evidence-based animal welfare practices simultaneously. Future research should prioritise multistressor experimental designs, molecular level characterisation of intervention mechanisms, and translational studies validating phytobiotic and microbiome-based strategies in commercial tropical production systems.

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