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Review of Evaluating Stress, Immunity, and Growth Performance of Beef Cattle Under Intensive Farming Systems

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Abstract
Intensive beef cattle farming systems are used to increase efficiency in meat production. However, these systems often cause animal welfare issues. Pressure from pen density, management practices, and environmental conditions can cause stress that directly impacts the health and growth of livestock. This article discusses the relationship between physiological stress levels, immune responses, and beef cattle growth in intensive systems, as well as the importance of proper management to support the sustainability of beef cattle farming. From previous studies, stress can be observed through increased cortisol hormone levels and changes in animal behavior. Immune responses can be determined through white blood cell counts, antibody levels, and vaccination effectiveness. Growth is usually assessed using parameters such as average daily gain (ADG), feed conversion ratio (FCR), and body condition score (BCS). Research also shows that high stress is negatively associated with the immune system, as seen in decreased antibodies and changes in blood profiles. In addition, high cortisol levels cause decreased food consumption, metabolic disorders, decreased feed efficiency, and decreased weight gain. In conclusion, management that prioritizes animal welfare, such as regulate stocking density, providing high-quality feed, and controlling stress, is a key factor.

INTRODUCTION

Beef cattle production plays a vital role in providing high-quality animal protein and supporting global food security. With the continuous growth of the human population and an increasing preference for meat consumption, the demand for beef has risen substantially. To address this challenge, many countries have implemented intensive beef cattle farming systems that aim to optimize feed efficiency, space utilization, and production rates (Gouvêa *et al.*, 2022; Hartono & Lestari, 2025). While these systems are designed to enhance productivity, they simultaneously expose animals to several stressors—including high stocking density, frequent handling, transportation, heat stress, and limited environmental enrichment which can negatively affect animal welfare and production outcomes (Siregar & Alam, 2024; Prasetyo & Rahayu, 2024).

Stress is a complex physiological and behavioral response triggered when animals perceive challenges that exceed their adaptive capacity. In cattle, the hypothalamic–pituitary–adrenal (HPA) axis acts as the primary regulator of stress responses by releasing corticotropin-releasing hormone (CRH) from the hypothalamus, which stimulates adrenocorticotropic hormone (ACTH) secretion from the pituitary gland, ultimately promoting cortisol synthesis in the adrenal cortex (Knezevic *et al.*, 2023). Cortisol serves as a critical biomarker of physiological stress and plays a central role in regulating metabolism, immune function, and energy mobilization. Short-term cortisol elevation can be adaptive; however, prolonged exposure common under intensive farming conditions induces chronic stress that suppresses immune function, alters metabolism, and impairs growth performance (Megahed *et al.*, 2023; Baraa *et al.*, 2025).

Recent studies emphasize that stress and immune function are closely interconnected. Elevated cortisol levels have been shown to suppress lymphocyte proliferation, reduce cytokine production, and impair antibody synthesis, leading to weakened immune responses and higher susceptibility to infections (Baraa *et al.*, 2025; Handayani & Yusuf, 2025). In intensively managed beef cattle, chronic stress alters hematological profiles characterized by leukocytosis, neutrophilia, and lymphopenia a pattern often referred to as a "stress leukogram." This immunosuppression reduces vaccine efficacy and the ability to respond to pathogens, compromising herd health and productivity (Gouvêa *et al.*, 2022). Moreover, high cortisol concentration has been associated with increased production of acute-phase proteins (APPs) such as haptoglobin (Hp) and serum amyloid A (SAA), which serve as sensitive biomarkers of systemic inflammation (Garcia-Torres *et al.*, 2021; Pagliasso *et al.*, 2023). The chronic elevation of APPs suggests ongoing physiological strain and reduced welfare status in cattle under intensive rearing conditions.

Stress also induces oxidative stress, which is characterized by an imbalance between the production of reactive oxygen species (ROS) and the antioxidant defense system of the body. This imbalance leads to lipid peroxidation, protein oxidation, and cellular damage, ultimately reducing metabolic efficiency and growth (Ayemele *et al.*, 2021). Recent evidence demonstrates that transportation and overcrowding significantly increase oxidative stress biomarkers such as malondialdehyde (MDA), while simultaneously decreasing concentrations of antioxidant vitamins such as vitamin E and selenium in the serum of stressed cattle (Handayani & Yusuf, 2025; Maulana & Sari, 2025). The accumulation of oxidative damage disrupts cellular metabolism and tissue repair, compounding the negative physiological effects of chronic stress. Therefore, the integration of antioxidant supplementation through dietary vitamin E, selenium, or natural phytogenic additives has been recommended to mitigate oxidative stress and strengthen immune resilience in beef cattle (Ayemele *et al.*, 2021; Huang *et al.*, 2023).

Beyond immunological alterations, stress has direct implications for growth performance and production efficiency. Chronic activation of the HPA axis increases gluconeogenesis and lipolysis, processes that divert energy from anabolic pathways toward survival mechanisms (Megahed *et al.*, 2023). As a result, average daily gain (ADG) decreases while feed conversion ratio (FCR) worsens, leading to inefficient feed utilization and economic losses. Furthermore, elevated cortisol interferes with the secretion and activity of anabolic hormones such as growth hormone (GH) and insulin-like growth factor-1 (IGF-1), thereby reducing protein synthesis and muscle accretion (Otten *et al.*, 2023). Studies in heat-stressed cattle have also shown decreased feed intake and nutrient absorption, resulting in slower weight gain despite adequate feed availability (Dahl *et al.*, 2020; Kim *et al.*, 2021). These findings confirm that chronic stress disrupts both physiological and behavioral mechanisms regulating growth.

The effects of stress extend beyond the production phase to influence meat quality. Pre-slaughter stress, characterized by elevated cortisol and catecholamine levels, leads to rapid glycogen depletion in muscle tissue and consequently produces meat with a high ultimate pH, dark color, and firm texture—known as Dark, Firm, Dry (DFD) meat (Lu *et al.*, 2018; Utami & Kurniawan, 2024). This condition not only reduces consumer acceptance but also shortens shelf life and increases post-harvest losses. Stress biomarkers such as Hp and SAA have been correlated with higher meat pH, suggesting that welfare management before slaughter is a key determinant of meat quality (Garcia-Torres *et al.*, 2021).

Addressing these challenges requires an integrative stress management strategy that combines environmental, nutritional, and behavioral approaches. Optimizing housing density, ventilation, and temperature control has been shown to reduce plasma cortisol and improve feed efficiency (Prasetyo & Rahayu, 2024; Hartono & Lestari, 2025). The implementation of environmental enrichment, such as providing sufficient space and visual barriers, reduces aggression and enhances natural behavior, contributing to lower stress levels (Wein *et al.*, 2024). Nutritional interventions—including antioxidant and trace mineral supplementation—also play a vital role in minimizing oxidative stress and supporting immune performance (Maulana & Sari, 2025; Huang *et al.*, 2023). Moreover, ethical handling practices and welfare-based management approaches are increasingly recognized as essential components of sustainable beef production (Shabtay, 2025; Hartono & Lestari, 2025).

In conclusion, stress represents a multifaceted challenge in modern beef production systems, influencing physiological, immunological, metabolic, and behavioral domains. Chronic stress not only suppresses immune function and compromises growth performance but also deteriorates meat quality and overall animal welfare. Understanding the mechanisms linking stress physiology, immunity, and growth is therefore critical for developing effective welfare-based management strategies. This synthesis highlights that sustainable beef cattle farming requires a balance between production efficiency and the well-being of the animals—ensuring that productivity gains do not come at the expense of health and ethical responsibility (Gouvêa *et al.*, 2022; Wein *et al.*, 2024; Megahed *et al.*, 2023).

RESEARCH METHODOLOGY

This study employed a literature review approach designed to synthesize recent scientific findings related to the effects of stress on immunity and growth performance in beef cattle raised under intensive production systems. The analysis focused on identifying physiological, biochemical, and behavioral indicators of stress and evaluating management interventions that mitigate its impact.

Data Collection and Selection

The literature search was using major academic databases including Scopus, PubMed, ScienceDirect, and Google Scholar. The search strategy combined key terms such as *"beef cattle stress," "intensive farming," "cortisol," "immune response," "oxidative stress,"* and *"growth performance."* Only peer-reviewed journal articles and proceedings published between 2015 and 2025 were considered to ensure scientific relevance and recentness.

The inclusion criteria were as follows:Studies focusing on beef cattle or closely related ruminant species reared under intensive systems,Research evaluating physiological or biochemical stress indicators such as cortisol, haptoglobin, serum amyloid A (SAA), or malondialdehyde (MDA),Papers analyzing the relationship between stress, immune response, and production parameters such as average daily gain (ADG), feed conversion ratio (FCR), or body condition score (BCS),andStudies assessing mitigation strategies involving environmental modification, nutritional supplementation, or animal welfare management.

Exclusion criteria included articles with insufficient methodological detail, studies on non-ruminant animals, or those focusing solely on meat processing without physiological analysis.

Data Extraction and Analysis

Each selected publication was critically evaluated for study design, experimental conditions, sample size, and key findings. The extracted data were grouped into three analytical themes:Physiological and hormonal responses to stress, focusing on cortisol and the HPA axis,Immunological and oxidative stress biomarkers, including leukocyte profiles, acute-phase proteins (Hp, SAA), antioxidant enzymes, and lipid peroxidation indicators (MDA),and Growth and performance outcomes, such as ADG, FCR, carcass yield, and meat quality.
The synthesis was qualitative, emphasizing the consistency and patterns across studies rather than statistical meta-analysis. Each variable's relationship was interpreted in the context of animal welfare and production efficiency.

Quality Assurance and Validity

To maintain objectivity, all data were cross-checked among co-authors, and the evaluation followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for scientific reviews. Priority was given to high-impact journals indexed in Scopus Q1–Q3. References were managed using Mendeley Desktop to ensure citation accuracy and consistency with the APA (7th edition) format required by IVAS proceedings.

Conceptual Framework

The conceptual basis of this review integrates three key domains:Stress Physiology – Activation of the HPA axis and increased cortisol secretion under intensive management conditions,Immune and Oxidative Balance – Alterations in white blood cell profiles, cytokine activity, and antioxidant status as indicators of stress-induced immunosuppression (Baraa *et al.*, 2025; Handayani & Yusuf, 2025),and Growth and Productivity Outcomes – The relationship between chronic stress, reduced anabolic hormone activity, and decreased feed efficiency and growth performance (Megahed *et al.*, 2023; Maulana & Sari, 2025).
This integrated approach enables the identification of physiological mechanisms linking stress to performance decline while highlighting management solutions such as improved housing conditions, environmental enrichment, and antioxidant supplementation (Wein *et al.*, 2024; Hartono & Lestari, 2025)

As this study was based solely on literature data, no experimental procedures involving live animals were conducted. However, all reviewed articles were required to comply with animal welfare and ethical research standards according to international guidelines. In summary, this methodological framework ensured that the review covered recent, scientifically valid, and practically relevant findings to provide a comprehensive understanding of how stress influences immune competence and growth in intensively reared beef cattle.

RESULTS AND DISCUSSION

Synthesis of Literature Findings

The literature review of 30 scientific sources published between 2018 and 2025 revealed that stress in beef cattle under intensive farming systems is a complex multifactorial phenomenon that influences physiological balance, immune competence, oxidative metabolism, and growth performance. Several consistent findings were identified across studies:(1.)Elevated cortisol and catecholamine levels serve as primary biomarkers of physiological stress and endocrine disruption (Megahed *et al.*, 2023; Knezevic *et al.*, 2023),(2.)Immune alterations, including increased acute-phase proteins (haptoglobin [Hp] and serum amyloid A [SAA]) and leukocyte profile shifts toward neutrophilia and lymphopenia (Pagliasso *et al.*, 2023; Baraa *et al.*, 2025).(3.)Oxidative imbalance, characterized by excessive malondialdehyde (MDA) formation and decreased antioxidant concentrations such as vitamin E and selenium (Ayemele *et al.*, 2021; Maulana & Sari, 2025).(4.)Reduced growth and feed efficiency, indicated by decreased average daily gain (ADG) and increased feed conversion ratio (FCR) (Gouvêa *et al.*, 2022; Kim *et al.*, 2021).(5.)Declining meat quality, with higher incidence of *Dark, Firm, Dry* (DFD) meat caused by pre-slaughter stress (Lu *et al.,* 2018; Utami & Kurniawan, 2024).

These findings collectively demonstrate that physiological stress in intensive systems affects multiple regulatory pathways, confirming the necessity of an integrated welfare-oriented management approach to sustain productivity and animal well-being.

Physiological Response to Stress

The physiological stress response in beef cattle is primarily governed by the hypothalamic–pituitary–adrenal (HPA) axis and the sympatho-adrenal medullary (SAM) system. When cattle experience environmental or social stressors—such as high stocking density, restricted movement, excessive handling, or heat load—the hypothalamus releases corticotropin-releasing hormone (CRH), stimulating adrenocorticotropic hormone (ACTH) secretion from the pituitary, which subsequently triggers cortisol release from the adrenal cortex (Knezevic *et al.*, 2023).

Short-term cortisol elevation facilitates adaptive responses by mobilizing glucose and fatty acids for immediate energy needs. However, prolonged activation of the HPA axis causes chronic hypercortisolemia, which suppresses immunity, impairs growth, and alters reproductive function (Megahed *et al.*, 2023). Persistent exposure to stressors diverts metabolic resources from anabolic to catabolic processes, reducing muscle accretion and nutrient utilization efficiency.

Otten *et al.* (2023) found that chronic cortisol exposure suppresses the secretion of growth hormone (GH) and downregulates insulin-like growth factor-1 (IGF-1) receptor expression in muscle tissues, resulting in impaired protein synthesis. Similarly, Widodo *et al.* (2023) reported that beef cattle raised under poor ventilation conditions exhibited increased body temperature, respiratory rate, and heart rate—physiological indicators of thermal stress and compromised homeostasis.

These findings confirm that the chronic activation of neuroendocrine stress pathways not only diminishes physiological efficiency but also predisposes animals to metabolic disorders and immune suppression.

Immunological and Inflammatory Responses

The interconnection between stress and immunity is mediated by glucocorticoid hormones, primarily cortisol. Elevated cortisol exerts immunosuppressive effects, inhibiting lymphocyte proliferation, suppressing cytokine production, and reducing antibody synthesis (Baraa *et al.*, 2025). As a result, stressed cattle display increased susceptibility to respiratory and enteric diseases commonly observed in feedlot environments (Megahed *et al.*, 2023).

Handayani and Yusuf (2025) demonstrated that heat-stressed cattle exhibited elevated levels of Hp and SAA—acute-phase proteins (APPs) induced by pro-inflammatory cytokines such as IL-6 and TNF-α. While acute inflammation is part of a normal defense mechanism, prolonged elevation of these markers reflects chronic systemic inflammation that drains energy reserves and diminishes immune responsiveness.

Pagliasso *et al.* (2023) noted that chronic stress produces a characteristic stress leukogram—increased neutrophil counts and reduced lymphocytes—indicating redistribution of immune cells from circulation to storage sites, which weakens adaptive immunity.

Furthermore, excessive cortisol inhibits macrophage activity, reducing phagocytic function and cytokine release.

Genetic factors also contribute to stress resilience. Garcia-Torres *et al.* (2021) reported that Retinta cattle exhibited significantly higher cortisol and Hp concentrations compared with other Spanish breeds under identical management, suggesting breed-specific variability in stress tolerance. These insights support the integration of genetic selection for stress-resistant phenotypes as a complementary welfare strategy in intensive beef production systems.

Oxidative Stress and Metabolic Consequences

Oxidative stress emerges as a central mechanism linking physiological and immunological alterations. Under stressful conditions, the generation of reactive oxygen species (ROS) exceeds the body's antioxidant capacity, leading to lipid peroxidation, protein oxidation, and cellular damage (Ayemele *et al.*, 2021). Maulana and Sari (2025) demonstrated that prolonged transportation stress doubled MDA levels in beef cattle while significantly reducing serum vitamin E and selenium concentrations—both vital antioxidants responsible for maintaining cellular membrane integrity.

The deficiency of these antioxidants disrupts the enzymatic defense network involving glutathione peroxidase (GPx) and superoxide dismutase (SOD), impairing mitochondrial energy production and increasing metabolic inefficiency. Huang *et al.* (2023) confirmed that dietary supplementation with organic selenium and vitamin E enhanced antioxidant enzyme activities by over 40% and reduced oxidative damage, ultimately improving growth rate and immune resilience.

Moreover, oxidative stress triggers mitochondrial dysfunction that limits ATP generation, forcing cattle to allocate more energy to cellular repair rather than growth. Hartono and Lestari (2025) emphasized that oxidative imbalance also compromises reproductive efficiency and muscle integrity, further illustrating its far-reaching economic and welfare implications. Thus, oxidative stress acts as a pivotal mediator translating environmental and management stressors into physiological inefficiency and performance decline.

Impact of Stress on Growth Performance

Chronic stress profoundly affects growth by altering endocrine signaling, appetite regulation, and nutrient metabolism. Elevated cortisol suppresses the release of GH and IGF-1, inhibits insulin secretion, and interferes with ghrelin pathways, resulting in decreased feed intake and anabolic activity (Megahed *et al.*, 2023; Otten *et al.*, 2023).

Gouvêa *et al.* (2022) reported that stressed cattle showed a 15–20% reduction in feed efficiency compared with animals managed under optimal welfare conditions. Similarly, Kim *et al.* (2021) observed that heat-stressed beef cattle reduced feeding activity by approximately 25% and exhibited an 18% increase in FCR despite equal energy availability.

These metabolic disturbances are further compounded by the redirection of energy toward stress adaptation, immune activation, and thermoregulation. As a result, less energy remains available for muscle protein synthesis and fat deposition. Dahl *et al.* (2020) also found that thermal stress disrupts nutrient absorption efficiency and alters digestive physiology, aggravating productivity losses.

Collectively, these findings illustrate that stress reduces not only voluntary feed intake but also the biological efficiency of nutrient utilization, leading to poorer growth performance and higher production costs per kilogram of body weight gain.

Effect of Stress on Meat Quality

Stress has profound implications for post-mortem muscle metabolism and meat quality traits. Pre-slaughter stress increases cortisol and catecholamine levels, which accelerate glycogen depletion in muscle tissues and reduce lactic acid production during post-mortem glycolysis (Lu *et al.*, 2018). Consequently, the ultimate meat pH remains high, producing Dark, Firm, Dry (DFD) meat characterized by dark color, firm texture, and reduced water-holding capacity.

Utami and Kurniawan (2024) confirmed that pre-slaughter handling stress in tropical beef cattle led to increased oxidative damage and inconsistent meat color, reducing consumer acceptability and shelf life. Garcia-Torres *et al.* (2021) also found a positive correlation between serum concentrations of Hp and SAA with ultimate pH, suggesting that these biomarkers can predict meat quality deterioration.

Oxidative stress in muscle tissues further accelerates lipid oxidation, causing rancidity and loss of color stability. These quality issues have significant economic implications, as DFD meat often results in financial penalties in commercial markets. Therefore, pre-slaughter management that minimizes stress—through gentle handling, adequate lairage time, and proper transport conditions—is essential to ensure both animal welfare and product quality.

Strategies for Stress Mitigation and Welfare Improvement

Managing stress in intensive beef cattle production requires an integrative approach combining environmental, nutritional, and behavioral interventions.(1.)Environmental control: Prasetyo and Rahayu (2024) demonstrated that optimizing stocking density and improving ventilation reduced plasma cortisol by 30% and enhanced feed efficiency. Widodo *et al.* (2023) similarly found that implementing shading systems, fans, and cooling pads effectively decreased core body temperature and physiological stress responses in tropical feedlots.(2.)Nutritional strategies: Antioxidant supplementation—including vitamin E, selenium, and plant-derived polyphenols—has been shown to enhance oxidative stability, strengthen immune defenses, and improve growth rates (Huang *et al.*, 2023; Maulana & Sari, 2025). Trace mineral injections and organic selenium sources further stabilize antioxidant enzyme activity, counteracting stress-induced metabolic disturbances (Megahed *et al.*, 2023).(3.)Behavioral and handling improvements: The adoption of *low-stress handling* practices—such as minimizing noise, using curved chutes, and training personnel in animal behavior—reduces acute cortisol spikes during movement and transport (Shabtay, 2025). These practices improve not only animal calmness but also carcass quality and worker safety.

Environmental enrichment plays an additional role in promoting natural behaviors and reducing aggression. Wein *et al.* (2024) reported that providing tactile brushes, visual barriers, and social grouping opportunities lowered cortisol levels and stimulated exploratory behavior in confined ruminants.

Hartono and Lestari (2025) highlighted that welfare-based management frameworks, when integrated into production goals, enhance productivity, sustainability, and consumer confidence in animal-derived food products. The shift toward welfare-conscious farming is thus both an ethical and economic imperative in modern livestock systems.

An Integrated Model for Sustainable Beef Cattle Production

Based on the synthesis of literature, the relationship between stress, immunity, and growth performance can be conceptualized through an integrated stress-response model encompassing four interlinked domains:(1.)Endocrine Response: Environmental and management stressors activate the HPA and SAM axes, increasing cortisol and catecholamine release, which mobilize energy but inhibit anabolic and immune functions,(2.)Immunological Response: Elevated cortisol leads to lymphopenia, increased acute-phase proteins, and systemic inflammation, reducing disease resistance and vaccine efficacy,(3.)Oxidative Response: Excess ROS generation depletes antioxidant reserves, causing cellular and mitochondrial damage that compromises metabolic efficiency,(4.)Production Outcomes: These combined effects reduce feed intake, worsen FCR, slow ADG, and deteriorate carcass and meat quality.

This framework underscores the necessity of addressing stress across hormonal, immune, and oxidative pathways simultaneously to achieve sustainable productivity. Integrating welfare standards and precision management technologies—such as real-time stress monitoring through cortisol biosensors or behavioral tracking—will enable early detection and prevention of chronic stress conditions.

Furthermore, the incorporation of genetic selection for stress-resilient breeds, combined with environmental optimization and nutritional fortification, provides a holistic pathway toward resilient and sustainable beef production systems. By aligning economic efficiency with animal welfare, producers can meet the growing global demand for ethically produced, high-quality beef without compromising livestock well-being or environmental responsibility.

Advanced Interpretation of Physiological and Behavioral Dynamics

The physiological and behavioral manifestations of stress in beef cattle are multifactorial and synergistic rather than isolated responses. Chronic activation of the hypothalamic–pituitary–adrenal (HPA) axis and the sympatho-adrenal medullary (SAM) system alters the homeostatic equilibrium of metabolic and immune pathways. In addition to cortisol, catecholamines such as adrenaline and noradrenaline intensify cardiovascular output and glucose mobilization, maintaining short-term survival at the cost of long-term efficiency (Knezevic *et al.*, 2023; Megahed *et al.*, 2023).

Prolonged stimulation of these pathways leads to metabolic exhaustion, where the energetic cost of maintaining allostasis surpasses adaptive capacity—an outcome termed *allostatic overload*. This concept explains why even moderate but sustained stressors (such as crowding or persistent noise) result in measurable declines in feed efficiency and growth (Gouvêa *et al.*, 2022). The feedback dysregulation of cortisol receptors in the hypothalamus and pituitary further perpetuates this state, maintaining high basal cortisol despite the absence of acute stimuli.

Behaviorally, stress manifests as restlessness, decreased rumination, altered posture, and reduced social interaction. Wein *et al.* (2024) emphasized that behavioral indicators—such as ear position, vocalization, and grooming frequency—serve as early warning signals of welfare deterioration. Thus, behavioral monitoring offers a low-cost diagnostic complement to physiological measures such as plasma cortisol or heart-rate variability.

Inter-Systemic Linkages: Endocrine–Immune–Metabolic Crosstalk

The intricate connection between endocrine, immune, and metabolic systems defines how stress translates into measurable production losses. Elevated cortisol simultaneously suppresses immune competence and induces insulin resistance, reducing glucose uptake in muscle tissue while promoting gluconeogenesis in the liver. This dual action diverts nutrients from productive metabolism toward maintenance, explaining the observed reductions in average daily gain (ADG) and feed efficiency (Otten *et al.*, 2023).

Moreover, stress-mediated inflammation and oxidative imbalance are tightly coupled. Pro-inflammatory cytokines (IL-6, TNF-α) activate nuclear factor kappa-B (NF-κB), a transcription factor that increases oxidative enzyme activity, enhancing reactive oxygen species (ROS) formation. In turn, ROS amplify cytokine signaling, forming a positive feedback loop that maintains chronic inflammation (Handayani & Yusuf, 2025). Breaking this loop requires interventions that target both oxidative and inflammatory pathways concurrently—such as antioxidant supplementation combined with anti-inflammatory management.

Additionally, recent studies indicate a role for the gut–brain axis in mediating stress responses. Alterations in ruminal microbiota under thermal or psychological stress disrupt short-chain fatty acid (SCFA) production, influencing both gut permeability and neuroendocrine feedback (Dahl *et al.*, 2020). This emerging evidence positions the rumen not only as a digestive organ but also as a regulatory interface for systemic stress adaptation.

Broader Implications for Growth and Productivity

Long-term stress does not simply delay growth but permanently alters the trajectory of productive performance. Muscle fiber hypertrophy and satellite cell proliferation, critical for carcass development, are hormonally suppressed by cortisol and inflammatory cytokines. Consequently, cattle subjected to chronic stress early in the finishing period exhibit lower slaughter weights even after subsequent recovery (Otten *et al.*, 2023).

Feed intake patterns are also disrupted by stress-mediated changes in appetite hormones. Elevated leptin and decreased ghrelin reduce hunger drive, while altered serotonin signaling affects feeding behavior (Megahed *et al.*, 2023). This hormonal imbalance not only decreases total dry-matter intake but also shortens feeding bouts, thereby reducing saliva production and impairing rumen buffering capacity. These physiological consequences highlight the importance of maintaining environmental stability to ensure consistent feeding behavior.

Stress-induced inefficiencies translate into substantial economic impacts. Based on aggregated findings from Gouvêa *et al.* (2022) and Baraa *et al.* (2025), average feed costs per kilogram of gain under chronic stress conditions increase by 12–18 %, primarily due to poorer feed conversion and higher maintenance energy demands. The resulting production inefficiencies directly reduce profitability and increase the carbon footprint per unit of beef produced.

Meat Quality and Post-Mortem Biochemistry: Extended Insights

Beyond its effect on growth, stress influences biochemical transformations that determine meat quality. Cortisol and catecholamines deplete muscle glycogen reserves, impairing lactic acid accumulation post-mortem. This limits pH decline and enhances the risk of DFD meat (Lu *et al.*, 2018). Furthermore, elevated oxidative stress during the pre-slaughter phase accelerates lipid oxidation, producing aldehydes responsible for rancid flavors and color instability (Garcia-Torres *et al.*, 2021).

Recent metabolomic analyses have identified that stress alters concentrations of *creatine phosphate*, *glucose-6-phosphate*, and *lactate dehydrogenase*—key intermediates in anaerobic metabolism. These shifts contribute to variability in meat tenderness and water-holding capacity. Utami and Kurniawan (2024) highlighted that providing animals a recovery rest period of at least 6–8 hours before slaughter normalizes these metabolites, yielding significantly improved sensory profiles.

Additionally, oxidative damage in muscle lipids leads to the formation of malondialdehyde (MDA), which serves as both a biomarker and a direct contributor to off-flavor development. Antioxidant supplementation with vitamin E has been shown to decrease MDA accumulation in post-mortem tissues by up to 45 %, directly improving color and flavor stability (Huang *et al.*, 2023). This evidence underlines that pre-slaughter nutritional management is as critical as post-slaughter handling in determining meat quality outcomes.

Sustainability and Welfare-Based Production

Modern beef production faces the dual challenge of maintaining productivity while ensuring environmental and ethical sustainability. Integrating animal welfare into production frameworks contributes to the triple bottom line—economic, environmental, and social. Welfare-oriented practices improve biological efficiency, reducing feed waste and greenhouse-gas emissions per unit of output (Hartono & Lestari, 2025).

Stress reduction is thus not merely an animal-centric objective but an environmental necessity. For instance, reducing heat stress through microclimate modification decreases respiration rate and methane emissions. Widodo *et al.* (2023) observed a 7 % reduction in methane production in cattle housed under misting and shading systems compared with those exposed to direct sunlight. Similarly, welfare-driven improvements in feed efficiency lower land and water requirements per kilogram of beef, aligning production with Sustainable Development Goals (SDGs 2, 12, and 13).

At the socio-economic level, welfare-based certification systems generate added market value. Consumers increasingly associate welfare assurance with product quality and safety, enhancing trust and brand reputation (Utami & Kurniawan, 2024). Therefore, welfare investment acts as a strategic business tool for accessing premium markets and ensuring long-term competitiveness.

Technological Innovations and Future Directions

Emerging precision technologies offer unprecedented opportunities for proactive welfare management. Real-time monitoring tools—including wearable biosensors for cortisol detection, heart-rate telemetry, and rumination trackers—enable early identification of stress events before performance decline occurs. Artificial intelligence (AI) systems analyzing behavioral and physiological data can automatically adjust ventilation, lighting, and feeding schedules to optimize comfort (Hartono & Lestari, 2025).

Furthermore, advancements in nutrigenomics provide insight into how diet composition influences gene expression under stress. Supplementation with omega-3 fatty acids, flavonoids, and organic trace minerals has been shown to upregulate antioxidant and immune-related genes, improving resilience at the molecular level (Maulana & Sari, 2025). Integrating such functional nutrition strategies could reduce reliance on pharmaceutical interventions, supporting more sustainable production.

Microbiome engineering represents another promising frontier. Manipulating ruminal microbial populations through targeted probiotics and prebiotics can enhance gut health and modulate the stress response via the gut–brain axis (Dahl *et al.*, 2020). Early evidence suggests that cattle receiving specific microbial consortia display lower cortisol and higher antioxidant enzyme activities, reflecting improved systemic balance.

Discussion Summary

In conclusion, evidence from the reviewed literature confirms that stress represents a critical constraint in intensive beef cattle systems, influencing physiological, immunological, oxidative, and productive domains. Elevated cortisol levels, oxidative imbalance, and chronic inflammation are central mechanisms linking stress to reduced growth performance and inferior meat quality.

However, these negative effects can be effectively mitigated through integrative management approaches that emphasize animal welfare. Proper housing conditions, ventilation control, antioxidant supplementation, and humane handling practices substantially reduce physiological strain, enhance feed efficiency, and improve overall productivity.

Ultimately, ensuring the welfare of beef cattle under intensive systems is not merely a moral responsibility—it is a prerequisite for long-term economic sustainability and food security. As consumer and regulatory demands for ethical production intensify, implementing welfare-based management will define the future of sustainable beef cattle farming

CONCLUSION AND SUGGESTION

Stress in intensive beef cattle systems significantly affects physiological balance, immune function, and growth performance, leading to reduced productivity and meat quality. Implementing welfare-based management—through environmental control, nutritional support, and ethical handling—effectively mitigates these impacts. Sustainable beef production therefore requires integrating animal welfare with productivity to ensure efficiency, profitability, and long-term food security.

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