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Strategies and advances in mitigating heat stress for lactating sows productivity

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Abstract
This review addresses the intricate challenges posed by heat stress on lactating sows within the context of swine production. As temperatures continue to rise globally, the physiological responses of lactating sows to heat stress, including thermoregulation, hormonal dynamics, and metabolic impacts, become increasingly critical. The exploration encompasses diverse facets, including ambient temperature, humidity, ventilation, and current management practices. Analyzing existing approaches reveals nutritional strategies, technological innovations, and dietary adjustments aimed at enhancing thermal resilience. Furthermore, advancements in cooling systems, smart farming solutions, and considerations for sow welfare are explored. The review extends to stress indicators, enrichment strategies, and genetic approaches, emphasizing the importance of holistic farm management. The complexities of selective breeding, genetic markers, and molecular tools are unveiled alongside reproductive and lactation management strategies. The discussion culminates in holistic farm management, success stories, and a forward-looking exploration of emerging technologies and unexplored frontiers in heat stress mitigation for lactating sows. This synthesis contributes to a nuanced understanding and strategic approach to ensure the well-being and productivity of lactating sows within the evolving landscape of contemporary swine production.

Keywords: Heat stress, Lactating sows, Thermoregulation, Environment, Nutrition, Genetic, Holistic farm

INTRODUCTION

The well-being and productivity of lactating sows in swine production are linked to the challenges posed by heat stress [1–3]. As global temperatures rise and climatic patterns become more unpredictable, the adverse effects of heat stress on these contributors to the industry demand comprehensive exploration and strategic solutions. Lactating sows are particularly susceptible to heat stress because milk production substantially increases metabolic heat load, exceeding the sow's capacity for thermoregulation under high ambient temperatures [4]. This review evaluates the multifaceted aspects of heat stress in lactating sows, encompassing physiological

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responses, environmental influences, existing mitigation approaches, and emerging strategies. Effects of dietary [5,6], technological [7,8], and genetic [9,10] interventions are essential to the intricate interplay of thermoregulation, hormonal dynamics, and environmental factors in order to have a holistic understanding of effective management practices. From the complexities of recognizing stress indicators to the successes and challenges in selective breeding, this exploration seeks to contribute to the evolving discourse on heat stress in lactating sows. In this review report, understanding the current knowledge, limitations, and unexplored territories will be discussed aiming to evaluate a resilient and sustainable future in swine production under the constraints of a changing climate.

Heat stress in lactating sows

The contextualization of heat stress in lactating sows within the domain of swine production elucidates a critical concern necessitating profound inquiry. Heat stress, arising from elevated ambient temperatures, instigates a cascade of intricate physiological responses in lactating sows, each facet underscoring the organisms endeavor to maintain homeostasis amidst thermal adversity [4,11]. Central to these adaptive mechanisms is the induction of heat shock protein (HSP), a conserved cellular defense mechanism activated in response to thermal stress [1,2,12]. HSPs, through their molecular chaperoning functions, mitigate protein denaturation and facilitate cellular repair, thereby safeguarding vital cellular structures and functions [1]. Concurrently, the endocrine system orchestrates an intricate response to heat stress, with cortisol emerging as a key player [13–15]. Elevated cortisol levels, indicative of the stress response, influence metabolic processes, in turn, modulate immune functions, emphasizing the systemic impact of heat stress [16,17]. Moreover, the thyroid hormone axis undergoes perturbations, influencing thermogenic processes and contributing to the overall metabolic recalibration observed during thermal stress [18,19]. The intersection of these molecular and endocrine responses underscores the nuanced nature of the physiological adaptations employed by lactating sows in the face of heat stress. Increased respiration rates, a consequence of thermal stress, further exacerbate metabolic demands, necessitating a delicate balance between respiratory and thermoregulatory functions [7,20]. In unraveling these intricate physiological responses, this exploration not only provides a foundational understanding of the challenges posed by heat stress but also serves as a precursor to the subsequent delineation of targeted mitigation strategies for sustaining optimal lactation performance in swine production systems.

Thermoregulation, hormones, and environmental influences

The thermoregulatory challenges confronted by lactating sows amid heat stress constitute a multifaceted interplay of physiological mechanisms essential for thermal homeostasis. Central to this paradigm is the thermoneutral zone, the temperature range wherein sows can maintain basal metabolic rates without expending energy on thermoregulatory efforts. Beyond this range, a series of adaptive responses ensue to dissipate excess heat. Vasodilation, a primary thermoregulatory mechanism, facilitates increased blood flow to peripheral tissues, promoting heat dissipation through convective and conductive processes [21]. Concurrently, the onset of sweating, albeit

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limited in swine, coupled with increased respiration rates, serves as an evaporative cooling mechanism crucial for thermal equilibrium [7,20,22]. These responses, orchestrated by the central nervous system and modulated by peripheral receptors [23], aim to counteract the deleterious effects of hyperthermia on cellular function.

Hormonal and metabolic impacts further underscore the systemic consequences of heat stress in lactating sows [17,22]. The hypothalamic-pituitary-adrenal (HPA) axis assumes a pivotal role, with the release of cortisol, the principal glucocorticoid, orchestrating adaptive responses [24]. While cortisol mobilizes energy reserves through gluconeogenesis and lipolysis [1,24], its chronic elevation poses a challenge, inducing catabolism and compromising nutrient utilization. The thyrotropic axis, concurrently affected, manifests alterations in thyroid hormone secretion, influencing metabolic rate and energy expenditure [22]. This intricate interplay of endocrine mediators implicates broader metabolic shifts, potentially compromising lactation efficiency.

Environmental factors influence the manifestation and severity of heat stress in lactating sows [3]. Ambient temperature and humidity enforce the thermal challenge faced by sows [7]. As ambient temperatures increase, the efficiency of convective and evaporative cooling diminishes, intensifying the strain on thermoregulatory mechanisms [11]. Ventilation assumes critical importance, with inadequate air exchange fostering the accumulation of heat and exacerbating thermal stress [25]. Consideration of air quality is often overlooked, as poor ventilation not only compromises thermal regulation but also exposes sows to respiratory challenges [7]. Environmental conditions strongly influence the thermoregulatory, hormonal, and metabolic responses of lactating sows, highlighting the need for clear strategies to alleviate the negative impacts of heat stress in swine production.

Ambient conditions, ventilation, and current management challenges

The interplay of ambient temperature and humidity profoundly influences the thermal comfort of lactating sows [3,26], necessitating an examination to comprehend the intricate physiological responses and inform adaptive management strategies. Elevated ambient temperatures, particularly in combination with high humidity levels increase the challenge in the sow ability to dissipate heat efficiently [27]. Thermoregulatory mechanisms, including vasodilation and evaporative cooling, become less effective during heat stress [9]. Consequently, a comprehensive understanding of the thermal thresholds and thermoneutral zones specific to lactating sows is important for devising targeted interventions. Ventilation and air quality, pivotal components of the microenvironment, exert influence on thermal dynamics [25]. Inadequate ventilation compromises the removal of heat and humidity, intensifying the thermal burden on sows [25]. Furthermore, suboptimal air quality, marked by elevated levels of ammonia and particulate matter, not only compromises respiratory health but also exacerbates heat stress by impeding efficient cooling mechanisms [7,19]. Effective ventilation strategies, encompassing airflow rates, directional control, and pollutant removal, thus emerge as pivotal elements in mitigating the adverse effects of heat stress on lactating sows.

Current management practices and challenges encapsulate a spectrum of considerations, spanning nutrition, housing, and husbandry protocols, each intricately linked to the overarching goal of alleviating heat stress in lactating sows [21]. Dietary strategies, tailored to augment thermotolerance, represent a central facet, with the inclusion of heat-mitigating additives and adjustments in nutrient composition aiming to enhance metabolic resilience. Management protocols necessitate synchronization with the physiological demands of lactation, requiring meticulous attention to reproductive scheduling and weaning strategies. Challenges persist in reconciling these multifaceted aspects [28], with limitations in existing approaches underscored by the need for integrated, interdisciplinary strategies. Consequently, a critical appraisal of current management practices, scrutinizing their efficacy in the context of heat stress, sets the stage for informed recommendations aimed at augmenting the thermal resilience of lactating sows within contemporary swine production paradigms.

Approaches, limits, and nutritional strategies for heat stress

An examination of existing approaches to mitigate heat stress in lactating sows emphasizes a critical analysis of the multifaceted strategies employed within the swine production paradigm. Existing interventions encompass a spectrum of modalities, spanning nutritional, environmental, and management domains, each striving to ameliorate the thermal challenges encountered by lactating sows [3,26]. However, an appraisal of these approaches reveals inherent limitations that underscore the complexity of mitigating heat stress. Environmental modifications, such as shade provision and improved ventilation, although impactful to some extent, but inadequate in alleviating the thermal burden during peak heat events [3,23]. Management practices, including altered reproductive schedules and weaning strategies, while contributing to stress reduction, pose logistical challenges and may compromise overall production efficiency.

In the realm of nutritional strategies for heat stress alleviation, the focus extends to the modulation of dietary composition and the incorporation of specific supplements tailored to enhance thermotolerance [1]. Nutritional interventions aim to address the increased metabolic demands imposed by heat stress and mitigate the associated catabolic effects. Strategic adjustments in nutrient composition, including alterations in protein, energy, fiber, and amino acid levels, serve to optimize nutrient utilization under thermal duress [1,29,30]. Additionally, the inclusion of feed additives, such as antioxidants, electrolytes, and direct-fed microbials, targets specific facets of the physiological response to heat stress [31,32]. Antioxidants, for instance, counteract oxidative stress induced by thermal challenges, while electrolytes aid in maintaining electrolyte balance compromised during increased respiration rates [31,32]. A thorough understanding of the mode of action of these nutritional strategies, at the molecular and metabolic levels, forms the crux of advancing targeted interventions [10,11,33]. Yet, limitations persist, necessitating ongoing research endeavors to refine nutritional protocols and devise innovative formulations that comprehensively address the intricate physiological dynamics underpinning heat stress in lactating sows.

Dietary resilience, supplements, feed additions, and technology

In the pursuit of enhancing thermal resilience in lactating sows, dietary adjustments stand as a pivotal avenue, leveraging intricate nutritional modulation to fortify metabolic capacities

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[1,5,29,34]. The optimization of nutrient composition, particularly focusing on energy and protein levels is geared towards mitigating the increased energy expenditure and catabolic effects induced by heat stress. Furthermore, the nuanced role of amino acids, such as arginine and glutamine, becomes pronounced, serving as precursors for nitric oxide production and contributing to the modulation of immune responses and vascular function [21,35]. Beyond macronutrient manipulation, micronutrients assume significance, with vitamins and minerals acting as cofactors in various enzymatic reactions implicated in thermoregulation and cellular homeostasis [9,36].

Concurrently, the role of nutritional supplements in enhancing thermal resilience unfolds as a distinctive facet. Antioxidants, including vitamins C and E, selenium, and carotenoids, operate at the cellular level, counteracting oxidative stress induced by thermal challenges [17,36]. Moreover, the inclusion of omega-3 fatty acids, notably eicosapentaenoic acid and docosahexaenoic acid, not only confers anti-inflammatory properties but also influences membrane fluidity, potentially ameliorating the deleterious effects of thermal stress on cellular structures [37–39]. Innovations in feed additives represent an evolving frontier, capitalizing on advancements in nutritional science and biochemistry. Probiotics and prebiotics, for instance, modulate the gut microbiota [40–42], fostering a symbiotic relationship that contributes to immune modulation and nutrient absorption. Direct-fed microbials, encompassing beneficial bacteria and yeast, operate through mechanisms such as competitive exclusion and immune stimulation, enhancing gastrointestinal health [43–45]. Phytogenic feed additives, derived from plants, showcase antioxidant and anti-inflammatory properties, further expanding the repertoire of nutritional strategies [46–48].

Cooling systems, smart farming, microenvironments, and welfare

Simultaneously, technological innovations in housing and facilities emerge as indispensable components against heat stress. Precision cooling systems, employing evaporative cooling pads and misting technologies, provide localized temperature control within housing structures [7,22,49]. Smart farming solutions, encompassing environmental sensors and automated climate control, enable real-time monitoring and adaptive adjustments, optimizing the microenvironment for sow well-being [50]. Additionally, the integration of thermography and precision livestock farming technologies facilitates early detection of thermal stress indicators, allowing for proactive interventions.

Advances in cooling systems represent a paradigm shift in the management of heat stress for lactating sows, leveraging technological innovation to optimize thermal comfort within housing structures [7,22,49]. Evaporative cooling pads, a cornerstone of modern cooling systems, facilitate efficient heat dissipation through the evaporation of water, effectively lowering the ambient temperature [7,22,49]. Complementary to this, misting technologies operate on the principles of adiabatic cooling, harnessing the heat absorption capacity of water droplets to reduce the overall temperature of the environment [7]. These systems, often integrated with precision climate control algorithms, enable fine-tuned adjustments to match sow-specific thermal requirements. Concurrently, smart farming solutions guide a transformative era in climate control, employing a network of environmental sensors and automated feedback mechanisms [9,51]. These sensors, measuring parameters such as temperature, humidity, and air quality, provide real-time data that informs adaptive adjustments in ventilation rates, cooling systems, and microenvironmental conditions. The integration of artificial intelligence algorithms further refines these systems, allowing for predictive modeling and proactive interventions to preemptively address impending heat stress challenges.

Optimizing microenvironments for lactating sows encompasses a holistic approach that extends beyond traditional cooling methods. Tailored housing designs, featuring shaded areas and strategic positioning of cooling apparatus, aim to create zones where sows can selectively seek thermal relief. Moreover, the introduction of adjustable microclimate zones within housing structures, facilitated by curtains or partitions, permits dynamic management of temperature gradients, accommodating the diverse thermal preferences of individual sows [10,52,53]. The optimization of flooring materials, incorporating heat-dissipating materials and providing comfortable resting areas, further contributes to enhancing the overall microenvironment and mitigating thermal stress.

Behavioral and welfare considerations emerge as intrinsic components in the discourse of heat stress management, emphasizing the psychological and physiological well-being of lactating sows [3,54,55]. Beyond the physiological manifestations, heat stress impacts the behavioral repertoire of sows, often leading to altered feeding patterns, reduced activity levels, and altered social interactions [55,56]. Recognizing these behavioral indicators becomes imperative for early detection and intervention. Enrichment strategies, encompassing the provision of manipulable materials and environmental stimuli, aim to mitigate stress through the promotion of natural behaviors. Additionally, considerations for space allowance and social dynamics within groups of lactating sows play a pivotal role in fostering a positive welfare state [57–59]. In the convergence of technological innovation, microenvironment optimization, and behavioral welfare considerations, a comprehensive approach to managing heat stress in lactating sows materializes, grounded in both scientific principles and ethical dimensions within contemporary swine production systems.

Stress recognition and enrichment strategies

Recognizing stress indicators in lactating sows is an important issue, requiring an in-depth understanding of both physiological and behavioral manifestations. Physiologically, heat stress induces alterations in hormonal profiles, with increased cortisol levels serving as a primary indicator of the stress response [7,13,60]. Furthermore, the activation of the HPA axis contributes to systemic physiological changes, including alterations in metabolic processes and immune functions [15,16]. Behaviorally, lactating sows exhibit shifts, including increased respiration rates, reduced feed intake, altered lying patterns, and heightened restlessness [1,5,7]. The integration of precision monitoring technologies, such as accelerometers and thermal imaging, allows for non-invasive, real-time assessment of these indicators. Enrichment strategies, designed to enhance the well-being of lactating sows, constitute a proactive approach in mitigating stressors. Environmental enrichment, encompassing the provision of manipulable materials, rooting

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substrates, and spaces conducive to exploratory behaviors, offers a means of stimulating cognitive engagement and attenuating stress responses [52,58]. Additionally, nutritional enrichment, involving the incorporation of palatable and varied diets, serves to not only address dietary preferences but also provide a sensory dimension to the sow's environment [4,61,62].

Selective breeding and genetic

Selective breeding for heat-tolerant traits represents a pivotal avenue in the ongoing pursuit of enhancing thermotolerance in lactating sows within the context of swine production. The foundational principle lies in the identification and prioritization of specific phenotypic traits that confer thermoregulatory advantages. Genetic approaches to heat resilience present a frontier rooted in selective breeding for thermotolerant traits [9,10,63]. Identifying genetic markers associated with heat resilience enables the targeted enhancement of adaptive mechanisms [9]. Polymorphisms related to thermoregulatory pathways, such as those involved in HSP or immune responses, offer potential avenues for genetic selection [63]. Integrating genomic tools and molecular breeding strategies allows for the systematic improvement of sow populations, fostering enhanced resilience to heat stress [9,63]. In the convergence of physiological monitoring, enrichment strategies, and genetic advancements, a multifaceted framework emerges for recognizing, mitigating, and preemptively addressing the deleterious effects of heat stress in lactating sows within the context of contemporary swine production. Traits encompassing both physiological and behavioral adaptations to heat stress are targeted, including increased HSP expression [12], efficient heat dissipation mechanisms [10], and altered thermoregulatory behaviors [3,55,56]. The integration of advanced genomic tools and molecular techniques facilitates the identification of heritable markers associated with these advantageous traits. Genome-wide association studies and quantitative trait loci analyses [8] unveil the genetic variants linked to heat resilience, providing a roadmap for selective breeding programs. Molecular tools, such as single nucleotide polymorphism markers, enable precise and efficient selection of desired traits, fostering accelerated progress in breeding programs [8].

Complementary to genetic advancements, management protocols and best practices emerge as indispensable components in mitigating the impact of heat stress on lactating sows. The strategic synchronization of reproductive cycles with environmental conditions, known as seasonal breeding management, allows for the optimization of lactation periods during mild climatic phases [9,10]. Additionally, strategic weaning practices, such as adapting weaning ages to align with periods of reduced heat stress [34], contribute to reducing the overall thermal burden on sows. Further, the implementation of heat abatement strategies within housing structures, including shade provision, adequate space allowance, and optimized ventilation, represents a synergy between genetic advancements and environmental management [9,58,63]. The integration of these multifaceted management protocols aligns with the broader goal of ameliorating the adverse effects of heat stress on lactating sows and underscores the necessity for a holistic approach that integrates genetic, environmental, and husbandry considerations within contemporary swine production paradigms.

Reproductive and lactation strategies

Reproductive and lactation management in heat-stressed environments necessitates an understanding of the interplay between the physiological demands of reproduction and the challenges imposed by thermal stress on lactating sows. Heat stress profoundly influences reproductive performance, as evidenced by disruptions in estrous expression, altered follicular development, and compromised oocyte quality [11,20]. Thermal stress during gestation further exacerbates these challenges, leading to reduced litter sizes and compromised fetal development [10,23]. In lactation, heat stress imposes additional burdens, manifesting as diminished milk production and altered composition, ultimately compromising the growth and vitality of piglets [20,61]. Consequently, comprehensive heat stress prevention strategies are essential to safeguard reproductive success and lactation efficiency. Precision cooling systems, strategically implemented within farrowing facilities, aim to create microenvironments that alleviate thermal stress during critical reproductive and lactation phases [7,49]. Moreover, nutritional interventions, tailored to the specific metabolic demands imposed by heat stress, serve to enhance the overall resilience of lactating sows [1,24,36]. Antioxidant supplementation, such as vitamin E and C, mitigates oxidative stress, preserving reproductive and lactation performance [17,36]. The inclusion of amino acids, particularly those influencing the production of neurotransmitters and hormones, aids in modulating stress responses [24,61]. Additionally, the integration of minerals, such as selenium, chromium and zinc, augments metabolic pathways implicated in thermal adaptation [17,64]. Integrated approaches, culminating in case studies, provide contextualized insights into the application and efficacy of multifaceted strategies. Case studies illuminate the intricate orchestration of genetic, nutritional, and environmental interventions within specific production systems, shedding light on the practical challenges and successes encountered. In unraveling these complexities, an academic discourse emerges, emphasizing the necessity of a holistic approach that amalgamates scientific understanding with practical applications to mitigate the multifactorial impact of heat stress on reproductive and lactating sows in modern swine production.

Holistic farm management

Holistic farm management strategies represent a multifaceted paradigm encompassing the integration of genetic, environmental, nutritional, and managerial facets to ameliorate the impact of heat stress on lactating sows within the broader context of swine production. These strategies pivot on the premise that addressing heat stress necessitates a comprehensive understanding of the interconnected factors influencing the sow's physiological responses to elevated temperatures. Genetic selection for thermotolerance, coupled with precision climate control systems, forms the genetic-environmental nexus, optimizing the microenvironment within housing structures [9,10,63]. Concurrently, nutritional strategies tailored to sow-specific metabolic demands contribute to the holistic approach by bolstering thermoregulatory efficiency and mitigating the systemic effects of thermal stress [21,24]. Successful farm management encompasses reproductive scheduling aligned with periods of reduced heat stress, strategic weaning protocols, and the incorporation of effective cooling measures [6]. Success performance in heat stress management provides insights into the tangible benefits of holistic strategies. These improvements in

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reproductive performance, enhanced sow welfare, and increased piglet vitality within specific production contexts [1,11]. However, despite these successes, future directions and research gaps necessitate continued inquiry to refine existing strategies and unearth novel approaches. The molecular underpinnings of thermotolerance, including the identification of additional genetic markers and pathways, remain areas ripe for exploration. Moreover, an in-depth understanding of the long-term implications of holistic interventions, spanning multiple reproductive cycles, is pivotal for the sustained success of such strategies. The integration of emerging technologies, such as artificial intelligence and advanced genomics, holds promise in revolutionizing heat stress management and improving resilient and sustainable future in swine production.

Emerging unexplored frontiers in heat stress

Emerging technologies and research frontiers in the domain of heat stress mitigation for lactating sows herald a paradigmatic shift, marked by the infusion of cutting-edge tools and innovative methodologies that delve into unexplored areas of physiological adaptation and environmental manipulation. On the forefront of research frontiers lies the application of advanced genomics, where high-throughput sequencing techniques, coupled with precision genome-editing technologies such as single-nucleotide polymorphism and genome-wide association studies, offer unprecedented opportunities for the identification and manipulation of specific genetic loci associated with heat resilience [8,65]. The integration of transcriptomics and metabolomics unveils intricate molecular pathways and metabolite signatures indicative of thermotolerance [2,12], providing a holistic understanding of the adaptive responses within the sow. Concurrently, the utilization of artificial intelligence and machine learning algorithms, harnessing large-scale datasets encompassing genotypic, phenotypic, and environmental parameters, facilitates predictive modeling of heat stress susceptibility and aids in the formulation of personalized interventions.

Environmental manipulation, guided by advancements in precision livestock farming, represents another unexplored frontier [18,20,52]. Real-time monitoring systems, equipped with environmental sensors and thermographic imaging, enable the assessment of thermal dynamics and sow well-being [18]. Moreover, the incorporation of microclimate modulation within housing structures, leveraging smart materials and adaptive control systems, allows for precise adjustment of temperature gradients, catering to the diverse thermal preferences of individual sows. The exploration of uncharted territories also extends to the microbiome, with investigations into the gut and skin microbiota fostering insights into the symbiotic relationships influencing immune function and thermoregulation.

Furthermore, the intersection of behavioral sciences and heat stress research unveils unexplored cognitive dimensions, delving into stress coping mechanisms, social dynamics, and the impact of enriched environments on sow behavior [3,54]. In this amalgamation of emerging technologies and research frontiers, the unexplored areas in heat stress mitigation manifest as intricate landscapes where molecular, environmental, and behavioral intricacies converge. Continued inquiry into these realms is pivotal for the holistic advancement of heat stress management strategies, offering a nuanced understanding of the physiological, genetic, and environmental nuances influencing the resilience of lactating sows within contemporary swine production paradigms.

CONCLUSION

In conclusion, mitigating heat stress in lactating sows demands a holistic strategy integrating nutritional, technological, genetic, and behavioral considerations. Physiological responses to elevated temperatures involve intricate mechanisms like vasodilation and hormonal modulation. Environmental factors such as temperature, humidity, and ventilation significantly impact heat stress severity. Strategies explored encompass dietary adjustments, technological innovations, genetic approaches, and behavioral considerations. Holistic farm management, combining these elements, shows tangible benefits in reproductive performance and sow welfare. Emerging technologies like genomics, artificial intelligence, and microbiome research offer new avenues. Future research must explore the long-term implications and sustainability of interventions. Integrating these advancements promises to reshape our understanding and management of heat stress in lactating sows, ensuring their well-being and productivity in modern swine production.

REFERENCES

1. Oh S, Hosseindoust A, Ha S, Moturi J, Mun J, Tajudeen H, et al. Metabolic responses of dietary fiber during heat stress: effects on reproductive performance and stress level of gestating sows. Metabolites. 2022;12:280. https://doi.org/10.3390/metabo12040280
2. He J, Guo H, Zheng W, Xue Y, Zhao R, Yao W. Heat stress affects fecal microbial and metabolic alterations of primiparous sows during late gestation. J Anim Sci Biotechnol. 2019;10:84. https://doi.org/10.1186/s40104-019-0391-0
3. Baert S, Aubé L, Haley DB, Bergeron R, Devillers N. The protective role of wallowing against heat stress in gestating and lactating sows housed outdoors. Physiol Behav. 2022;254:113898. https://doi.org/10.1016/j.physbeh.2022.113898
4. Tummaruk P, De Rensis F, Kirkwood RN. Managing prolific sows in tropical environments. Mol Reprod Dev. 2023;90:533-45. https://doi.org/10.1002/mrd.23661
5. Shang Q, Liu S, Liu H, Mahfuz S, Piao X. Impact of sugar beet pulp and wheat bran on serum biochemical profile, inflammatory responses and gut microbiota in sows during late gestation and lactation. J Anim Sci Biotechnol. 2021;12:54. https://doi.org/10.1186/s40104-021-00573-3
6. Moturi J, Hosseindoust A, Tajudeen H, Mun JY, Ha SH, Kim JS. Influence of dietary fiber intake and soluble to insoluble fiber ratio on reproductive performance of sows during late gestation under hot climatic conditions. Sci Rep. 2022;12:19749. https://doi.org/10.1038/s41598-022-23811-8
7. Silva BAN, Oliveira RFM, Donzele JL, Fernandes HC, Abreu MLT, Noblet J, et al. Effect of floor cooling on performance of lactating sows during summer. Livest Sci. 2006;105:176-84. https://doi.org/10.1016/j.livsci.2006.06.007
8. Tajudeen H, Moturi J, Hosseindoust A, Ha S, Mun J, Choi Y, et al. Effects of various cooling methods and drinking water temperatures on reproductive performance and behavior in heat stressed sows. J Anim Sci Technol. 2022;64:782-91. https://doi.org/10.5187/jast.2022.e33

 https://doi.org/10.5187/ait.2400022

9. Shi L, Li Y, Liu Q, Zhang L, Wang L, Liu X, et al. Identification of SNPs and candidate genes for milk production ability in yorkshire pigs. Front Genet. 2021;12:724533. https://doi.org/10.3389/fgene.2021.724533
10. Gourdine JL, Mandonnet N, Giorgi M, Renaudeau D. Genetic parameters for thermoregulation and production traits in lactating sows reared in tropical climate. Animal. 2017;11:365-74. https://doi.org/10.1017/S175173111600135X
11. Black JL, Mullan BP, Lorschy ML, Giles LR. Lactation in the sow during heat stress. Livest Prod Sci. 1993;35:153-70. https://doi.org/10.1016/0301-6226(93)90188-N
12. Ni Y, Wu F, Chen Q, Cai J, Hu J, Shen J, et al. Long noncoding RNA and mRNA profiling of hypothalamic-pituitary-mammary gland axis in lactating sows under heat stress. Genomics. 2020;112:3668-76. https://doi.org/10.1016/j.ygeno.2020.04.021
13. Nejad JG, Sung KI. Blood hormone profiles, physiological variables, and behavioral criteria in Corriedale ewes fed different TMR moisture levels during thermal–humidity exposure. Biol Rhythm Res. 2018;49:382-91. https://doi.org/10.1080/09291016.2017.1362095
14. Nejad JG, Ataallahi M, Park KH. Methodological validation of measuring Hanwoo hair cortisol concentration using bead beater and surgical scissors. J Anim Sci Technol. 2019;61:41-6. https://doi.org/10.5187/jast.2019.61.1.41
15. Ataallahi M, Nejad JG, Park KH. Selection of appropriate biomatrices for studies of chronic stress in animals: a review. J Anim Sci Technol. 2022;64:621-39. https://doi.org/10.5187/jast.2022.e38
16. Ghassemi Nejad J, Kim BW, Lee BH, Sung KI. Coat and hair color: hair cortisol and serotonin levels in lactating Holstein cows under heat stress conditions. Anim Sci J. 2017;88:190-4. https://doi.org/10.1111/asj.12662
17. Kim KY, Hosseindoust A, Choi YH, Kim MJ, Lee JH, Kim TG, et al. Hot-melt extruded selenium: a highly absorbable nano-selenium in lactating sows exposed to high ambient temperature. Biol Trace Elem Res. 2021;199:3345-53. https://doi.org/10.1007/s12011-020-02459-3
18. Quiniou N. Results of 15 years of precision feeding of hyper prolific gestating sows. Animals. 2021;11:2908. https://doi.org/10.3390/ani11102908
19. Rigo EJ, Antunes RC, Mundim AV, Gonçalves FC, Guimarães EC, Nascimento MRBM. Effect of two cooling systems on thyroid hormones and thermophysiological variables of lactating sows. Arq Bras Med Vet Zootec. 2019;71:1853-60. https://doi.org/10.1590/1678-4162-11158
20. Vilas Boas Ribeiro BP, Lanferdini E, Palencia JYP, Lemes MAG, Teixeira de Abreu ML, de Souza Cantarelli V, et al. Heat negatively affects lactating swine: a meta-analysis. J Therm Biol. 2018;74:325-30. https://doi.org/10.1016/j.jtherbio.2018.04.015
21. Liu F, de Ruyter EM, Athorn RZ, Brewster CJ, Henman DJ, Morrison RS, et al. Effects of L-citrulline supplementation on heat stress physiology, lactation performance and subsequent reproductive performance of sows in summer. J Anim Physiol Anim Nutr. 2019;103:251-7. https://doi.org/10.1111/jpn.13028
22. Ricci GD, da Silva-Miranda KO, Titto CG. Infrared thermography as a non-invasive method for the evaluation of heat stress in pigs kept in pens free of cages in the maternity. Comput Electron Agric. 2019;157:403-9. https://doi.org/10.1016/j.compag.2019.01.017
23. He J, Zheng W, Lu M, Yang X, Xue Y, Yao W. A controlled heat stress during late gestation affects thermoregulation, productive performance, and metabolite profiles of primiparous sow. J Therm Biol. 2019;81:33-40. https://doi.org/10.1016/j.jtherbio.2019.01.011
24. Choi Y, Hosseindoust A, Shim Y, Kim M, Kumar A, Oh S, et al. Evaluation of high

nutrient diets on litter performance of heat-stressed lactating sows. Asian-Australas J Anim Sci. 2017;30:1598-604. https://doi.org/10.5713/ajas.17.0398
25. Brandt P, Bjerg B, Pedersen P, Sørensen KB, Rong L, Huang T, et al. The effect of air temperature, velocity and humidity on respiration rate and rectal temperature as an expression of heat stress in gestating sows. J Therm Biol. 2022;104:103142. https://doi.org/10.1016/j.jtherbio.2021.103142
26. Cabezón FA, Schinckel AP, Marchant JN, Johnson JS, Stwalley RM. Effect of floor cooling on late lactation sows under acute heat stress. Livest Sci. 2017;206:113-20. https://doi.org/10.1016/j.livsci.2017.10.017
27. Johnson JS, Wen H, Freitas PHF, Maskal JM, Hartman SO, Byrd M, et al. Evaluating phenotypes associated with heat tolerance and identifying moderate and severe heat stress thresholds in lactating sows housed in mechanically or naturally ventilated barns during the summer under commercial conditions. J Anim Sci. 2023;101:skad129. https://doi.org/10.1093/jas/skad129
28. Johnson JS, Jansen TL, Galvin M, Field TC, Graham JR, Stwalley RM, et al. Electronically controlled cooling pads can improve litter growth performance and indirect measures of milk production in heat-stressed lactating sows. J Anim Sci. 2022;100:skab371. https://doi.org/10.1093/jas/skab371
29. Choi Y, Moturi J, Hosseindoust A, Kim M, Kim K, Lee J, et al. Night feeding in lactating sows is an essential management approach to decrease the detrimental impacts of heat stress. J Anim Sci Technol. 2019;61:333-9. https://doi.org/10.5187/jast.2019.61.6.333
30. Schoenherr WD, Stahly TS, Cromwell GL. The effects of dietary fat or fiber addition on yield and composition of milk from sows housed in a warm or hot environment. J Anim Sci. 1989;67:482-95. https://doi.org/10.2527/jas1989.672482x
31. Hosseindoust A, Oh SM, Ko HS, Jeon SM, Ha SH, Jang A, et al. Muscle antioxidant activity and meat quality are altered by supplementation of astaxanthin in broilers exposed to high temperature. Antioxidants. 2020;9:1032. https://doi.org/10.3390/antiox9111032
32. Moura CS, Lollo PCB, Morato PN, Amaya-Farfan J. Dietary nutrients and bioactive substances modulate heat shock protein (HSP) expression: a review. Nutrients. 2018;10:683. https://doi.org/10.3390/nu10060683
33. Zhang S, Johnson JS, Trottier NL. Effect of dietary near ideal amino acid profile on heat production of lactating sows exposed to thermal neutral and heat stress conditions. J Anim Sci Biotechnol. 2020;11:75. https://doi.org/10.1186/s40104-020-00483-w
34. Farmer C. Review: mammary development in swine: effects of hormonal status, nutrition and management. Can J Anim Sci. 2013;93:1-7. https://doi.org/10.4141/cjas2012-066
35. Pérez Laspiur J, Farmer C, Kerr BJ, Zanella A, Trottier NL. Hormonal response to dietary L-arginine supplementation in heat-stressed sows. Can J Anim Sci. 2006;86:373-81. https://doi.org/10.4141/A06-015
36. Liu F, Cottrell JJ, Collins CL, Henman DJ, O'Halloran KSB, Dunshea FR. Supplementation of selenium, vitamin E, chromium and betaine above recommended levels improves lactating performance of sows over summer. Trop Anim Health Prod. 2017;49:1461-9. https://doi.org/10.1007/s11250-017-1348-y
37. Lin S, Hou J, Xiang F, Zhang X, Che L, Lin Y, et al. Reproductive stage associated changes in plasma fatty acid profile and proinflammatory cytokine expression in rat mammary glands. Anim Nutr. 2016;2:119-26. https://doi.org/10.1016/j.aninu.2016.03.008
38. Llauradó-Calero E, Badiola I, Samarra I, Lizardo R, Torrallardona D, Esteve-Garcia E, et

al. Eicosapentaenoic acid- and docosahexaenoic acid-rich fish oil in sow and piglet diets modifies blood oxylipins and immune indicators in both, sows and suckling piglets. Animal. 2022;16:100634. https://doi.org/10.1016/j.animal.2022.100634
39. Taugbøl O, Framstad T, Saarem K. Supplements of cod liver oil to lactating sows: influence on milk fatty acid composition and growth performance of piglets. J Vet Med Ser A. 1993;40:437-43. https://doi.org/10.1111/j.1439-0442.1993.tb00650.x
40. Moturi J, Kim KY, Hosseindoust A, Lee JH, Xuan B, Park J, et al. Effects of Lactobacillus salivarius isolated from feces of fast-growing pigs on intestinal microbiota and morphology of suckling piglets. Sci Rep. 2021;11:6757. https://doi.org/10.1038/s41598-021-85630-7
41. Choi Y, Goel A, Hosseindoust A, Lee S, Kim K, Jeon S, et al. Effects of dietary supplementation of Ecklonia cava with or without probiotics on the growth performance, nutrient digestibility, immunity and intestinal health in weanling pigs. Ital J Anim Sci. 2016;15:62-8. https://doi.org/10.1080/1828051X.2015.1128685
42. Kim JS, Hosseindoust A, Lee SH, Choi YH, Kim MJ, Lee JH, et al. Bacteriophage cocktail and multi-strain probiotics in the feed for weanling pigs: effects on intestine morphology and targeted intestinal coliforms and Clostridium. Animal. 2017;11:45-53. https://doi.org/10.1017/S1751731116001166
43. Hosseindoust AR, Lee SH, Kim JS, Choi YH, Kwon IK, Chae BJ. Productive performance of weanling piglets was improved by administration of a mixture of bacteriophages, targeted to control Coliforms and Clostridium spp. shedding in a challenging environment. J Anim Physiol Anim Nutr. 2017;101:e98-107. https://doi.org/10.1111/jpn.12567
44. Hosseindoust A, Park JW, Kim IH. Effects of Bacillus subtilis, Kefir and β-glucan supplementation on growth performance, blood characteristics, meat quality and intestine microbiota in broilers. Korean J Poult Sci. 2016;43:159-67. https://doi.org/10.5536/KJPS.2016.43.3.159
45. Kim M, Hosseindoust A, Choi Y, Lee J, Kim K, Kim T, et al. Effects of hot-melt extruded nano-copper as an alternative for the pharmacological dose of copper sulfate in weanling pigs. Biol Trace Elem Res. 2021;199:2925-35. https://doi.org/10.1007/s12011-020-02426-y
46. Serpunja S, Abdolreza H, Kim IH. A mixture of thyme, quillaja, and anise at different nutrient density on growth performance, nutrient digestibility, meat quality, organ weight, cecal bacteria, excreta moisture, and bone contents in broiler chicks. Korean J Poult Sci. 2017;44:151-9. https://doi.org/10.5536/KJPS.2017.44.3.151
47. Mohammadi Gheisar M, Hosseindoust A, Kim IH. Evaluating the effect of microencapsulated blends of organic acids and essential oils in broiler chickens diet. J Appl Poult Res. 2015;24:511-9. https://doi.org/10.3382/japr/pfv063
48. Jiao Y, Hosseindoust A, Zhang WL, Kim IH. Effects of salicornia herbacea on growth performance, meat quality, excreta microbial populations, and noxious gas emissions in broiler chicks. J Poult Sci. 2019;56:44-51. https://doi.org/10.2141/jpsa.0170210
49. Maskal J, Cabezón FA, Schinckel AP, Marchant-Forde JN, Johnson JS, Stwalley RM. Evaluation of floor cooling on lactating sows under mild and moderate heat stress. Prof Anim Sci. 2018;34:84-94. https://doi.org/10.15232/pas.2017-01661
50. Van JCF, Tham PE, Lim HR, Khoo KS, Chang JS, Show PL. Integration of Internet-of-Things as sustainable smart farming technology for the rearing of black soldier fly to mitigate food waste. J Taiwan Inst Chem Eng. 2022;137:104235. https://doi.org/10.1016/j.jtice.2022.104235
51. Dourmad JY, Le Velly V, Gourdine JL, Renaudeau D. Effect of ambient temperature in

lactating sows, a meta-analysis and simulation approach in the context of climate change. Anim Open Space. 2022;1:100025. https://doi.org/10.1016/j.anopes.2022.100025

52. Kim KH, Hosseindoust A, Ingale SL, Lee SH, Noh HS, Choi YH, et al. Effects of gestational housing on reproductive performance and behavior of sows with different backfat thickness. Asian-Australas J Anim Sci. 2016;29:142-8. https://doi.org/10.5713/ajas.14.0973
53. Bjerg B, Brandt P, Pedersen P, Zhang G. Sows' responses to increased heat load: a review. J Therm Biol. 2020;94:102758. https://doi.org/10.1016/j.jtherbio.2020.102758
54. Zhu Y, Johnston LJ, Reese MH, Buchanan ES, Tallaksen JE, Hilbrands AH, et al. Effects of cooled floor pads combined with chilled drinking water on behavior and performance of lactating sows under heat stress. J Anim Sci. 2021;99:skab066. https://doi.org/10.1093/jas/skab066
55. Liu L, Tai M, Yao W, Zhao R, Shen M. Effects of heat stress on posture transitions and reproductive performance of primiparous sows during late gestation. J Therm Biol. 2021;96:102828. https://doi.org/10.1016/j.jtherbio.2020.102828
56. do Nascimento Mós JV, Nascimento ST, Murata LS, dos Santos VM, Neto AJS, de Oliveira EM, et al. Thermal comfort of sows in free-range system in Brazilian Savanna. J Therm Biol. 2020;88:102489. https://doi.org/10.1016/j.jtherbio.2019.102489
57. Agyekum AK, Nyachoti CM. Nutritional and metabolic consequences of feeding high-fiber diets to swine: a review. Engineering. 2017;3:716-25. https://doi.org/10.1016/J.ENG.2017.03.010
58. Bench CJ, Rioja-Lang FC, Hayne SM, Gonyou HW. Group gestation housing with individual feeding—I: how feeding regime, resource allocation, and genetic factors affect sow welfare. Livest Sci. 2013;152:208-17. https://doi.org/10.1016/j.livsci.2012.12.021
59. Meunier-Salaün MC, Edwards SA, Robert S. Effect of dietary fibre on the behaviour and health of the restricted fed sow. Anim Feed Sci Technol. 2001;90:53-69. https://doi.org/10.1016/S0377-8401(01)00196-1
60. Ghassemi Nejad J, Lee BH, Kim JY, Kim BW, Chemere B, Park KH, et al. Comparing hair cortisol concentrations from various body sites and serum cortisol in Holstein lactating cows and heifers during thermal comfort zone. J Vet Behav. 2019;30:92-5. https://doi.org/10.1016/j.jveb.2018.12.007
61. Kim K, Choi Y, Hosseindoust A, Kim M, Hwang S, Bu M, et al. Evaluation of high nutrient diets and additional dextrose on reproductive performance and litter performance of heat-stressed lactating sows. Anim Sci J. 2019;90:1212-9. https://doi.org/10.1111/asj.13214
62. Lee SH, Hosseindoust AR, Kim JS, Choi YH, Lee JH, Kwon IK, et al. Bacteriophages as a promising anti-pathogenic option in creep-feed for suckling piglets: targeted to control Clostridium spp. and coliforms faecal shedding. Livest Sci. 2016;191:161-4. https://doi.org/10.1016/j.livsci.2016.08.003
63. Freitas PHF, Johnson JS, Wen H, Maskal JM, Tiezzi F, Maltecca C, et al. Genetic parameters for automatically-measured vaginal temperature, respiration efficiency, and other thermotolerance indicators measured on lactating sows under heat stress conditions. Genet Sel Evol. 2023;55:65. https://doi.org/10.1186/s12711-023-00842-x
64. Oh SM, Kim MJ, Hosseindoust A, Kim KY, Choi YH, Ham HB, et al. Hot melt extruded-based nano zinc as an alternative to the pharmacological dose of ZnO in weanling piglets. Asian-Australas J Anim Sci. 2020;33:992-1001. https://doi.org/10.5713/ajas.19.0140
65. Gutiérrez B, Domingo-Calap P. Phage therapy in gastrointestinal diseases. Microorganisms. 2020;8:1420. https://doi.org/10.3390/microorganisms8091420

 https://doi.org/10.5187/ait.2400022