

Reproduction as a key component of animal welfare: Conceptual foundations for sustainable livestock farming

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Abstract. Modern global livestock farming is undergoing transformative changes driven by the need to implement the principles of sustainable development, ethical farming and high standards of animal welfare. For a long time, in animal science and practice, reproductive performance has been assessed primarily through the prism of economic efficiency and production intensification, whilst its significance as an indicator of the biological, physiological and psycho-emotional state of animals has remained insufficiently explored. The aim of the study was to provide a theoretical justification and to develop a comprehensive conceptual model of reproduction as a key component of farm animal welfare to ensure the long-term sustainability of the livestock sector. The methodology of the study was based on the application of systemic-structural analysis, scientific generalisation, comparison and conceptual modelling of the results of contemporary fundamental and applied research indexed in the

Article's History:

Received: 05.05.2026 Revised: 01.09.2026 Accepted: 29.09.2026 Published: 07.10.2026

Suggested Citation:

Skliarov, P., Vakulik, V., Mylostyvyi, R., Bilyi, D., & Koreyba, L. (2026). Reproduction as a key component of animal welfare: Conceptual foundations for sustainable livestock farming. *Ukrainian Black Sea Region Agrarian Science*, 30(3), 54-73. doi: 10.56407/bs.agrarian/3.2026.54.

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scientometric databases Scopus and Web of Science. As a result of the study, the neuroendocrine and physiological mechanisms of reproductive function suppression under the influence of technological and environmental stress, caused by the activation of the hypothalamic-pituitary-adrenal axis and elevated cortisol levels, were detailed. Causal links have been established between poor housing conditions, chronic stress and delayed recovery of the oestrous cycle following parturition. The importance of the expression of natural reproductive and maternal behaviour as a key indicator of the formation of a positive emotional state in animals within the context of the modern Five Domains model has been substantiated. A conceptual framework has been developed that integrates reproductive health parameters, behavioural responses and technological factors into a unified system for assessing animal welfare. The practical significance of the results lies in the development of scientifically grounded approaches to adapting technological processes in animal husbandry, enabling the effective combination of a high level of animal welfare with their reproductive capacity and the long-term economic efficiency of farming

Keywords: reproductive health; Five Domains model; technological stress; maternal behaviour; physiological resilience

INTRODUCTION

Modern livestock production aims to simultaneously ensure productivity, animal health, an adequate level of animal welfare and the long-term sustainability of production systems. In this context, there is an increasing shift from assessing production efficiency primarily through productive performance indicators towards a comprehensive consideration of animal condition and the consequences of the technologies employed. L.G. Keeling (2025) analysed the relationship between animal welfare and the Sustainable Development Goals and showed that welfare should be regarded as a component of sustainable livestock production rather than as its opposite. The author emphasised the possibility of combining welfare indicators with environmental, economic and other sustainability indicators to identify potential synergies and trade-offs.

An important area of current research is the refinement of methods for directly assessing the condition of animals. J. Linstädt *et al.* (2024) conducted a systematic review of animal-based welfare indicators for dairy cows and assessed their validity and practicality. The authors demonstrated that welfare assessment should be based on a set of complementary indicators relating to the animals' health, physical condition, behaviour and living conditions. The findings confirm the need for a comprehensive approach, in which no single indicator is considered sufficient to characterise overall welfare. The expansion of this approach involves taking into account not only negative but also positive states of the animals. N. Beausoleil *et al.* (2023) analysed the application of the Five Domains model to animal welfare management within the food chain. The researchers demonstrated that the model allows for the systematisation of the impact of nutrition, the physical environment, health and behavioural interactions on an animal's condition, whilst the fifth domain links these

factors to positive and negative mental experiences. Thus, the Five Domains model broadens the assessment of welfare from the control of adverse factors to an analysis of the animal's overall experience.

The methodological rationale for a comprehensive assessment of welfare was presented by F. Van der Staay *et al.* (2025), who systematised current definitions, conceptual frameworks and tools for assessing animal welfare. The authors emphasised the need to align the theoretical definition of welfare with methods for its practical measurement and proposed a multi-level approach to assessment. This is of fundamental importance for research into reproductive health, as it allows reproductive indicators to be considered not in isolation but within the context of the animal's overall functional state. At the same time, an animal's condition is largely determined by the characteristics of the production system. S. Nielsen *et al.* (2023) carried out a comprehensive assessment of the welfare of dairy cows and analysed the main risk factors in various housing systems. The authors examined locomotor disorders, mastitis, restricted mobility, problems with rest, the fulfilment of behavioural needs, and metabolic disorders. The results showed that welfare assessment should focus not only on the characteristics of the housing technology, but primarily on its actual effects on the animal's physiology and behaviour.

An important complement to this approach is the assessment of the role of digital technologies in monitoring animal condition. G. Papakonstantinou *et al.* (2024) analysed the capabilities of precision livestock farming technologies for monitoring animal health and welfare and demonstrated their potential for the automated collection of behavioural and physiological data. At the same time, the authors highlighted the need to take into account the technological,

ethical and environmental aspects of digitalisation. This confirms the value of combining automated monitoring with traditional veterinary assessment of animal condition. A separate area of current research concerns the link between welfare and reproductive function. S. LeBlanc (2023) summarised current data on postpartum diseases and fertility in dairy cows and demonstrated that reproductive outcomes are closely linked to the animal's health status around the time of calving. The author emphasised the interdependence of postpartum diseases, physiological stress and subsequent reproductive performance. These findings support the view that reproductive function is the result of a complex interplay between health, physiological state and housing conditions.

P. Skliarov *et al.* (2022) analysed the impact of heat stress on the reproductive performance of dairy cows at various physiological stages, in particular during pregnancy, calving and the postpartum period. The authors found that increased thermal stress has a negative effect on reproductive performance, reduces fertility and may increase the risk of forced culling. According to the authors, timely reduction of heat stress, adjustments to the diet and the selection of animals with increased heat tolerance are important strategies for preventing reproductive losses. In their study, R. Carrasco & K. Breen (2023) analysed the mechanisms of allostasis through which the body adapts to various stressors. The authors demonstrated that temperature, metabolic, immune and psychosocial factors can influence the neuroendocrine control of reproduction, in particular through changes in the activity of neurons involved in the regulation of gonadotropin-releasing hormone. According to the authors, the suppression of reproductive function under conditions of acute stress is one of the adaptive mechanisms aimed at preserving the organism's viability.

M. Jensen *et al.* (2023) investigated the effect of postpartum housing arrangements on maternal behaviour in cows and the formation of the bond between cow and calf. The authors compared the behaviour of cow-calf pairs in individual calving pens with an open and a partially enclosed area, which provided the opportunity for seclusion after calving. It was found that the provision of such an area encouraged more frequent licking of calves by the mother and enhanced displays of maternal behaviour, particularly during the first 24 hours after birth. The authors concluded that creating conditions for the expression of natural maternal behaviour can help to form a bond between the cow and the calf and improve their welfare. B. Mirzaie *et al.* (2024) investigated the impact of organisational and technological solutions, housing systems and veterinary care

on the reproductive performance of dairy cows. The authors analysed 136,943 records relating to 21,756 cows and assessed the relationship between the duration of the voluntary waiting period, housing conditions, heat stress and indicators such as the number of days to first insemination, the service interval and the number of inseminations per conception. It was found that the housing system was significantly associated with fertility: cows in loose-housing systems had better reproductive outcomes compared with those in open sheds. The authors concluded that optimising management decisions and housing conditions is a key component in improving the reproductive efficiency of the dairy herd.

A. Sinnott *et al.* (2024) investigated the effects of full, partial and no contact between cows and their calves on health, behaviour, calf growth and labour costs in pasture-based dairy production systems. The study compared three housing systems: constant contact between the cow and calf on pasture, partial contact indoors, and no contact. It was found that contact with the cow promoted higher growth rates in calves prior to weaning and reduced labour costs during calving; however, constant contact on pasture was associated with an increased risk of health problems in calves and higher weekly labour costs. Under partial contact, the authors noted more frequent instances of abnormal behaviour and a negative impact on growth after weaning. The authors concluded that none of the systems provided a clear advantage across all assessed indicators; therefore, the organisation of cow-calf contact requires a comprehensive consideration of animal welfare and practical production conditions.

Thus, an analysis of contemporary research indicates that the reproductive function of dairy cows is closely associated with housing conditions, feeding, the level of heat and other forms of stress, health status, behavioural manifestations and the opportunity to express natural social interactions. Studies across different fields demonstrate that unfavourable environmental conditions and impaired adaptive mechanisms may adversely affect reproductive performance, whereas optimisation of feeding, the microclimate, housing systems and monitoring technologies contributes to maintaining animal health and productivity. At the same time, contemporary approaches to welfare assessment increasingly focus on the comprehensive consideration of physical health, behaviour, emotional state and the opportunity for animals to express their natural needs. Thus, the available scientific evidence supports considering reproduction not merely as a production indicator but as an important component of overall animal welfare, thereby justifying the further development of an integrated conceptual model of the relationship

between reproductive function and welfare in sustainable livestock farming. The aim of the study was to substantiate a conceptual model of reproduction as a key component of the welfare of farm animals and to elucidate its significance for ensuring the sustainability of the livestock sector.

MATERIALS AND METHODS

The study was conducted as a theoretical and conceptual review aimed at systematising current scientific understanding of the relationship between welfare, physiological status and reproductive function in farm animals and, on this basis, developing a conceptual framework for integrating reproduction into the animal welfare assessment system. The information base of the study consisted of scientific publications indexed in the international bibliographic databases Scopus and Web of Science. The literature search focused primarily on publications from 2010-2025. However, earlier studies of fundamental theoretical importance were also considered when describing the historical development of specific concepts, particularly the Five Domains Model, and explaining fundamental physiological mechanisms.

The literature search was conducted using thematic groups of keywords and their combinations with the Boolean operators AND and OR. The main search queries included the following combinations: “animal welfare” AND reproduction; “reproductive health” AND “farm animals”; “technological stress” AND reproduction; “chronic stress” AND fertility; “Five Domains Model” AND animal welfare; “animal welfare” AND maternal behaviour; “transition period” AND reproduction AND dairy cattle; “stress physiology” AND reproductive function; “cortisol” AND fertility AND livestock; “precision livestock farming” AND animal welfare AND reproduction. Additional searches were conducted using specific terms related to individual mechanisms through which stress affects reproductive function, including “hypothalamic-pituitary-adrenal axis” AND reproduction, “oxidative stress” AND oocyte, “inflammation” AND fertility, and “metabolic stress” AND reproductive performance.

For the content analysis, peer-reviewed original research articles, systematic and narrative reviews, meta-analyses and conceptual papers were specifically selected if they met at least one of the defined thematic criteria: contained data on the effects of housing conditions or technological or environmental stressors on the physiological status of animals; characterised changes in reproductive function in relation to stress, disease, metabolic disorders or behavioural responses; considered reproductive indicators as a component of health or welfare; contained data on maternal behaviour, early separation of dams and offspring, or other

behavioural aspects of reproduction; or assessed the potential for digital monitoring of behavioural, physiological or reproductive indicators.

This selection process took the form of a thematic and content-based analysis of the scientific literature and did not involve a quantitative meta-analysis or the establishment of a statistical inclusion and exclusion flowchart for publications. The main inclusion criterion was the source's relevance to the task of theoretically substantiating the relationship between welfare, stress, reproductive function and the sustainability of livestock farming. The analysis excluded publications that did not relate to farm animals or did not allow the results to be extrapolated to livestock farming systems; studies without a clearly described methodology; materials lacking the full text or where it was impossible to assess the reliability of the results; duplicates; and sources whose content did not allow a link to be established between technological factors, the body's physiological response and reproductive function.

The selected publications were analysed across several interrelated areas: animal species, the nature of the technological or environmental factor, the type of stress response, physiological and metabolic markers, behavioural changes, reproductive consequences, and the potential for using the relevant indicators to assess welfare. Separately, when analysing the selected sources, data were systematised regarding neuroendocrine, molecular-genetic, immune and metabolic indicators used by the authors of the original studies to characterise the mechanisms underlying reproductive dysfunction. This group included indicators of the activity of the hypothalamic-pituitary-gonadal axis and its associated signalling pathways (Kiss1, LHCGR, 3 β -HSD, CYP19A1, CYP17A1), pro-inflammatory mediators (TNF- α , IL-1 β , IL-6), markers of oocyte function and early embryonic development, in particular interferon- τ , as well as metabolic parameters, including β -hydroxybutyrate and calcium. These parameters were not measured directly within the scope of this study, but were used as evidence-based markers, as described in the selected publications, to establish causal links between stress, metabolic and immune disorders, and reproductive function.

In addition, data from the selected publications were summarised regarding the environmental and economic consequences of changes in reproductive efficiency, in particular indicators of greenhouse gas emissions, feed conversion efficiency, the need for replacement young stock, productive longevity and the economic sustainability of production. These indicators were considered exclusively as secondary indicators of sustainability, as reported in the relevant studies and models, and were not calculated directly by the authors

of this study. Their inclusion in the conceptual model was achieved through a comparative and systematic synthesis of the published results. The object of the study was the relationship between animal welfare status and reproductive health in farm animals under modern technological housing systems. The subject of the study comprised the causal and feedback relationships between technological and environmental factors, the stress response of the organism, neuroendocrine, metabolic, immune and behavioural indicators, and the functional state of the reproductive system.

The scope of application of the conceptual framework developed covered industrial and intensive livestock farming systems. The main evidence base consisted of studies conducted on dairy cattle, as it is for this species that the relationships between technological and environmental factors, physiological status, behaviour, welfare and reproductive function have been studied in the greatest detail. At the same time, the conceptual model was developed taking into account general biological mechanisms that may potentially be relevant to other species of farm animals. The application of the model to other species within the scope of this study was not considered to be empirically confirmed, but is identified as a direction for further interspecies adaptation and validation.

The conceptual model was developed sequentially in four stages. At the first stage, external technological and environmental factors capable of adversely affecting animal welfare and reproductive function were identified. These included unbalanced feeding, negative energy balance, heat stress, overcrowding, restricted locomotor activity, disruption of group social structure, inadequate housing conditions, pain syndromes, disease, negative human-animal interactions and technological interventions that restrict the expression of natural behaviour. At the second stage, the physiological mechanisms through which external influences are transformed into an internal adaptive response of the organism were identified. Particular attention was given to activation of the hypothalamic-pituitary-adrenal axis, changes in cortisol concentration, disruption of the hypothalamic-pituitary-gonadal system, development of negative energy balance, systemic inflammation, oxidative stress and immunometabolic dysfunction. At the third stage, the functional consequences of these physiological changes for the reproductive system were identified. These included delayed restoration of reproductive cyclicity after parturition, reduced expression of oestrus, impaired ovulation, reduced oocyte quality, reduced fertility, early embryonic mortality, development of postpartum disorders and reduced reproductive longevity. At the fourth stage, the identified

relationships were integrated into a unified conceptual system in which reproductive indicators were considered not merely as production outcomes but as an integrated manifestation of the interaction between the technological environment, physiological status and psycho-emotional well-being of the animal.

The conceptual framework was developed using systems-structural analysis, scientific synthesis, comparison and conceptual modelling. Causal relationships were analysed according to the following sequence: technological or environmental stressor → physiological adaptive response → changes in neuroendocrine, metabolic, immune and behavioural indicators → impaired reproductive function → deterioration of the animal's overall welfare status and productive longevity. Particular attention was given to the role of the hypothalamic-pituitary-adrenal axis as one of the key mechanisms linking external housing conditions with reproductive function. An increase in cortisol concentration was not regarded as an independent universal indicator of welfare but as a physiological marker of the stress response, the significance of which should be interpreted in conjunction with behavioural, metabolic, immune and reproductive indicators. Feedback relationships within the system were also analysed separately. Impaired reproductive function, postpartum diseases, pain, metabolic disorders and reduced locomotor activity may, in turn, increase stress load and adversely affect animal welfare. Thus, the interaction between the technological environment, physiological status, reproductive function and welfare is not linear but cyclical, involving mutually reinforcing and compensatory feedback mechanisms. The conceptual framework was based on the assumption that changes in reproductive indicators can serve as informative indicators of impaired biological adaptation only when interpreted comprehensively alongside indicators of health, behaviour, physiological status and housing conditions. This approach was used to integrate reproduction into the broader system of animal welfare assessment.

RESULTS AND DISCUSSION

Neuroendocrine, immunometabolic and epigenetic mechanisms of reproductive suppression

Modern intensive livestock farming technologies are often accompanied by complex stressors. The reproductive system is one of the physiological systems most sensitive to chronic stress; therefore, disturbances in its functioning are often one of the early signs of deteriorating housing conditions, changes in the technological environment or a decline in animal welfare (Kaiser & Jaillardon, 2023). Under such conditions, impaired fertility should be regarded not only as a consequence of

stress, but also as an adaptive physiological response reflecting the prioritisation of survival mechanisms

over the fulfilment of reproductive function (Evans & Anderson, 2023; Carrasco & Breen, 2023) (Fig. 1).

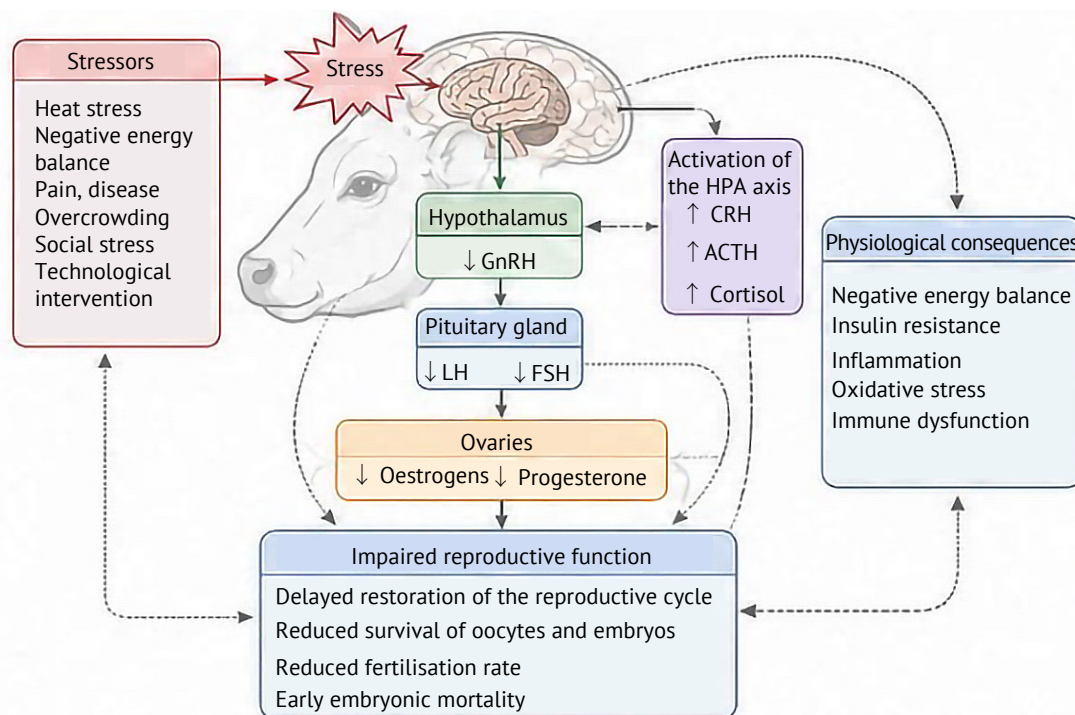


Figure 1. Neuroendocrine mechanisms of the effects of technological stress

Source: compiled by the authors

The physiological basis of the body's initial response to a technological or environmental stressor is the activation of the hypothalamic-pituitary-adrenal axis (Herman *et al.*, 2002). In response to the stressor, there is a sequential secretion of corticotropin-releasing hormone and adrenocorticotrophic hormone, leading to a systemic increase in the concentration of cortisol and other glucocorticoids in the circulating blood. High levels of glucocorticoids exert a marked inhibitory effect on the hypothalamic-pituitary-gonadal axis at several interrelated levels (Bhaumik *et al.*, 2023; Kaiser & Jaillardon, 2023; Martinez *et al.*, 2024). At the hypothalamic level, increased glucocorticoid concentrations may disrupt the function of Kiss1 neurons, which are involved in regulating GnRH secretion and, consequently, LH. Experimental studies have shown that chronic stress reduces the expression of Kiss1 and Kisspeptin in the hypothalamus, increases cortisol levels and is accompanied by impairments in reproductive function; these effects are partly mediated by the glucocorticoid receptors of Kiss1 neurons (Huang *et al.*, 2022). At the pituitary level, cortisol directly reduces the anterior pituitary's response to GnRH, which manifests as inhibition of LH secretion; this effect has been demonstrated, in particular, in experiments with bovine anterior

pituitary cells and in sheep models (Breen *et al.*, 2005). At the ovarian level, activation of the stress axis is accompanied by impaired steroidogenesis in pre-ovulatory follicles. In cows, experimental administration of ACTH, accompanied by an increase in cortisol concentration, reduced the levels of oestradiol and androstenedione in follicular fluid, as well as the expression of the LHCGR, 3 β -HSD, CYP19A1 and CYP17A1, which was associated with impaired ovulation and the formation of persistent or cystic follicles (Biran *et al.*, 2015).

The development of production-related stress is almost always accompanied by profound metabolic changes. In high-yielding animals, a negative energy balance at the start of lactation is accompanied by intense lipolysis and the accumulation of free fatty acids and ketone bodies in the blood. This metabolic distress is closely linked to a disruption of immune homeostasis (Proudfoot, 2023; Van Saun, 2023). Chronic stress and digestive disorders, in particular subacute ruminal acidosis, can increase the permeability of the intestinal-ruminal barrier, facilitating the translocation of bacterial lipopolysaccharides (endotoxins) into the systemic circulation. A review of current data on ruminal LPS suggests that their accumulation and translocation may be associated with the activation of the immune response and

the development of systemic inflammatory reactions (Sarmikasoglou & Faciola, 2022). In cows with subacute ruminal acidosis, elevated concentrations of LPS in the rumen and blood have been observed, along with the activation of pro-inflammatory signalling pathways and increased production of tumour necrosis factor- α , interleukins-1 β and -6 (Zhao *et al.*, 2018). The systemic effects of LPS and pro-inflammatory mediators may disrupt the neuroendocrine regulation of reproductive function and adversely affect the functioning of the reproductive organs. At the ovarian level, LPS and TNF- α are capable of altering the gene expression of oocytes and cumulus cells during their maturation, indicating a disruption in the function of the follicular microenvironment and a reduction in oocyte quality (Piersanti *et al.*, 2019). An additional mechanism underlying reproductive disorders is the development of oxidative stress. Under conditions of heat stress, the production of reactive oxygen species and the level of oxidative stress increase in oocytes and early embryos of cattle, accompanied by a reduction in the rate of cleavage and blastocyst formation, as well as impaired production of interferon- τ (Amaral *et al.*, 2020). Thus, the inflammatory response, impaired function of oocytes and cumulus cells, and oxidative damage may form an interrelated complex of mechanisms through which metabolic and heat stress adversely affect the reproductive performance of cattle.

The most distant and potentially harmful consequence of chronic stress is epigenetic reprogramming (Zhu *et al.*, 2021). Maternal state of stress during oocyte maturation, fertilisation and early embryogenesis can alter patterns of DNA methylation and histone modifications in germ cells and embryonic tissues without changing the nucleotide sequence itself

(Eleftheriou *et al.*, 2022; Qian & Guo, 2022). Epigenetic modifications disrupt the establishment and functioning of the hypothalamic-pituitary-adrenal and gonadal axes in the developing foetus (Bansal & Simmons, 2018; Al'Absi *et al.*, 2021). This creates a transgenerational effect, whereby offspring of stressed mothers are born with reduced adaptive capacity, increased reactivity to stressors and a predisposition to reduced reproductive capacity in adulthood (Aiken & Ozanne, 2014; Mbiydenyuy *et al.*, 2022; Das *et al.*, 2023). Thus, neuroendocrine, immunometabolic and epigenetic changes, taken together, form a coherent pathogenic chain. Disruption in any of these links is direct evidence of a breach in biological homeostasis and a low level of animal welfare.

Behavioural markers, motherhood and environmental factors in the context of the Five Domains model

Traditional approaches to assessing the welfare of farm animals have long been based predominantly on veterinary and sanitary criteria and the absence of clinical signs of disease. The modern concept of animal welfare is based on a comprehensive assessment of their biological condition, which encompasses physical health, behavioural responses, environmental conditions and the animal's psycho-emotional state (Mellor *et al.*, 2020; van der Staay *et al.*, 2025). In this context, behavioural responses and other biological indicators are regarded as important characteristics of an organism's adaptation to housing conditions. The Five Domains Model enables a systematic analysis of how disturbances in environmental conditions and technological factors may translate into suppression of reproductive function through changes in the locomotor and mental state of animals (Fig. 2).

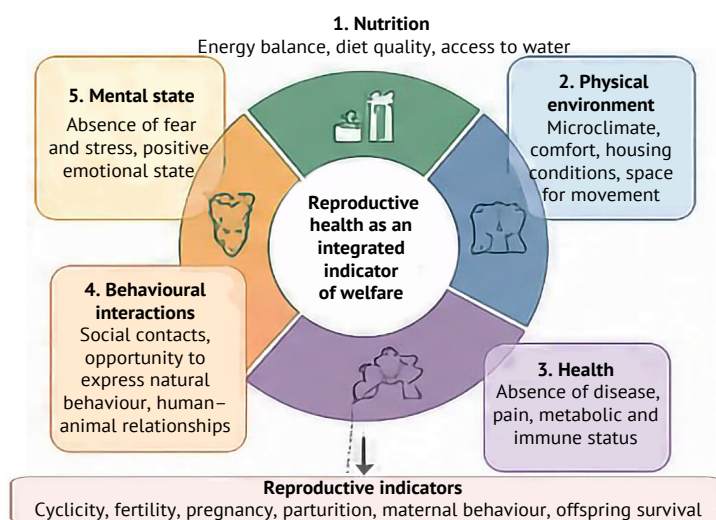


Figure 2. Integration of reproductive indicators into the Five Domains Model

Source: developed by the authors

The first domain – nutrition and hydration – covers the supply of water and nutrients to animals, which are essential for maintaining metabolic processes and reproductive function. An unbalanced diet, insufficient water intake, deficiencies in macro- and micronutrients, and a negative energy balance can lead to the depletion of the body's metabolic reserves and disrupt the energy supply to the reproductive system, which can block follicular maturation and inhibit oestrogen secretion, contributing to the development of ovarian hypofunction and anoestrus (Ambrose, 2021; Song *et al.*, 2021). The second domain – the physical environment – characterises the conditions in which the animal is kept, in particular resting comfort, the quality of the flooring, stocking density, and temperature and humidity conditions. Slippery or hard flooring, poor-quality bedding, restricted space and an unfavourable microclimate can cause discomfort, reduce locomotor activity and alter animal behaviour, which complicates the manifestation of natural signs of oestrus and the timely detection of animals in oestrus (Cerri *et al.*, 2021; Palomares, 2021).

The third domain – health – relates to the presence or absence of diseases, pathological processes and pain conditions. The presence of subclinical pathologies, inflammatory processes in the reproductive system and limb disorders can lead to chronic pain syndrome. Prolonged pain is accompanied by activation of the hypothalamic-pituitary-adrenal axis and increased cortisol secretion, which can disrupt the neuroendocrine regulation of the oestrous cycle and adversely affect reproductive function (Wrzecińska *et al.*, 2021). The fourth domain – behavioural interactions and autonomy – reflects an animal's ability to express natural social, locomotor and reproductive behaviours. Restrictions on locomotor activity, a lack of social interactions, and competition for food and resting places can hinder the expression of species-specific behaviour, limit animals' ability to make choices and control their own behavioural interactions, and contribute to the development of negative affective states and chronic social stress (Mellor *et al.*, 2020). Thus, animals' ability to respond appropriately to environmental conditions and fulfil their natural behavioural and reproductive needs is impaired.

The fifth domain – mental state – is the integrated result of the influence of factors represented in the first four domains. A combination of negative affective states, in particular pain, anxiety and exhaustion, is accompanied by the activation of stress-mediating neuroendocrine mechanisms, which may inhibit the functioning of the hypothalamic-pituitary-gonadal axis and, thus, reproductive function (Mellor *et al.*, 2020). Thus, the interaction of nutritional and hydration disorders,

adverse physical environmental conditions, deteriorating health, restrictions on natural behaviour and negative mental states forms a complex pathophysiological mechanism through which a decline in animal welfare may manifest as impairments in reproductive function. A separate important aspect of female welfare is ensuring the opportunity to express natural maternal behaviour. However, in modern intensive livestock systems, it is common practice to wean newborn calves from their mothers early, and often almost immediately after birth, in order to simplify husbandry practices and ensure production efficiency. Despite the production advantages of such a system, a growing body of research considers the restriction of contact between a cow and calf to be a significant welfare issue, as it limits the opportunity to express natural behaviour and may affect the behavioural and productive performance of calves (Sinnott *et al.*, 2024).

Physiological and behavioural studies indicate that early separation of the mother and newborn is accompanied by acute behavioural and physiological stress responses in both animals, manifested by increased vocalisation, search behaviour and other signs of distress. The neuroendocrine response to early separation is associated with the activation of stress mechanisms, whilst the maintenance of maternal-offspring contact ensures the expression of natural behavioural interactions and the associated neuroendocrine responses. Depriving the mother of the opportunity to lick and feed her offspring, and the newborn of the opportunity to suckle, can lead to a high frequency of vocalisations, motor restlessness, and an increase in the frequency of defecation and urination. In young animals, early separation and restrictions on the ability to engage in suckling behaviour may contribute to the development of abnormal behaviours, in particular inter-nipple suckling and suckling on pieces of equipment. At the same time, sensory stimulation during contact between the mother and her offspring plays a role in regulating the oxytocinergic system, which is associated with the development of maternal behaviour and postpartum uterine activity. Thus, the nature of the interaction between the mother and her offspring may influence not only the behavioural and mental state of the animals, but also the neuroendocrine mechanisms associated with postpartum recovery of reproductive function.

A decline in welfare and the presence of chronic stress significantly alter the classic behavioural pattern of oestrus. Instead of pronounced oestrus behaviour, animals often exhibit a reduction in the intensity or a complete absence of behavioural signs of oestrus (silent oestrus), and there is an increased frequency of ovulatory disorders and anovulatory cycles. Key

behavioural markers of impaired welfare and reproductive function in females are considered to be reduced locomotor activity, changes in the duration of lying down, reduced feed intake, attenuated or absent behavioural signs of oestrus, impaired social interaction, and the development of lameness. It is precisely these indicators that are widely used in Precision Livestock Farming systems for the early detection of welfare issues and reproductive disorders (Papageorgiou & Simitzis, 2022; Smolík *et al.*, 2024). A reduction in the intensity of sexual behaviour may manifest, in particular, as suppression of the immobility reflex when other animals are in heat and a decrease in overall motor activity and locomotion during the anticipated oestrus period. At the same time, a reduction in chewing duration and a decrease in feed intake may indicate a shift in behavioural balance towards stress-related responses, which potentially reduces the expression of sexual behaviour (Papageorgiou & Simitzis, 2022; Smolík *et al.*, 2024). The use of modern digital systems for automated behavioural monitoring, in particular accelerometers, movement activity sensors, collar-mounted sensors and vocalisation analysis systems, enables the continuous recording of animals' behavioural characteristics and allows for a more objective assessment of changes in their behavioural budget (Smolík *et al.*, 2024). This approach creates opportunities for the timely detection of early changes associated with impaired welfare, the development of stress, diseases and reproductive disorders, even before the appearance of pronounced clinical signs (Jurkovich *et al.*, 2024; Leliveld *et al.*, 2024; Linstädt *et al.*, 2024).

The impact of technological management and digitalisation on reproduction and welfare

The resilience of the reproductive system and the level of animal welfare in industrial production settings are largely determined by the quality of technological management (Jurkovich *et al.*, 2024; Linstädt *et al.*, 2024). The man-made environment can serve both as a source of chronic stress and as a means of minimising biological risks. Management decisions directly influence the physiological status of animals during the most vulnerable periods of the production cycle (Carulla *et al.*, 2023; EFSA AHAW Panel (EFSA Panel on Animal Health and Animal Welfare) *et al.*, 2023). Interpersonal interactions between care staff and animals form what are known as human-animal relationships, which are an important component of the animal welfare system (Field *et al.*, 2024). The nature of these relationships directly affects behavioural and physiological responses in animals and the activity of the neuroendocrine system, particularly the

hypothalamic-pituitary-adrenal axis, and may also influence reproductive function through stress-mediated mechanisms (Waiblinger & Lürzel, 2023). In the case of negative interactions, the use of rough restraint methods, shouting, aversive herding techniques and painful stimuli can lead to the development of a persistent fear response towards humans in animals. Such interaction is accompanied by activation of the sympathetic-adrenal system and the hypothalamic-pituitary-adrenal axis, manifested by increased secretion of adrenaline, noradrenaline and cortisol. With prolonged exposure to stressors, the activation of neuroendocrine mechanisms may suppress reproductive function due to disruption of the regulation of gonadotrophin-releasing hormone (GnRH) and luteinising hormone (LH), potentially leading to disruption of the oestrous cycle, reduced oestrus expression, impaired ovulation and reduced fertility. In contrast, a positive type of interaction, based on calm, predictable and consistent behaviour on the part of staff, the use of a calm voice and regular positive contact with the animals, promotes the formation of positive human-animal relationships and reduces fear responses and stress levels. This is accompanied by a reduction in the activity of the hypothalamic-pituitary-adrenal axis and cortisol concentrations, facilitates veterinary and zootechnical procedures, in particular artificial insemination, and may indirectly contribute to improved reproductive performance (Marçal-Pedroza *et al.*, 2023). Thus, the quality of human-animal relationships is an important behavioural and technical factor which, through the regulation of the stress response, can influence the welfare and reproductive efficiency of farm animals.

Technological factors in management and their impact on the transition period

The most critical stage in the life of high-yielding dairy cows is the transition period, which traditionally spans three weeks before and three weeks after calving. It is during this time that the most intense physiological, endocrine, metabolic and immune changes take place in the animal's body, which determine its subsequent health, welfare, reproductive function and productivity (Emam *et al.*, 2025). Errors in management practices during this period may be directly linked to the occurrence of postpartum complications. Frequent transfers of animals between management groups disrupt the established social hierarchy, provoke agonistic interactions, increase competition for feed and may alter the daily time budget (Carulla *et al.*, 2023; Proudfoot, 2023). Under such conditions, social stress may be accompanied by a reduction in dry matter intake, which exacerbates the negative energy balance during the transition

period. In turn, a pronounced negative energy balance is a significant risk factor for the development of postpartum metabolic and reproductive disorders, reduced fertility and a deterioration in the overall health of cows (Pavlenko *et al.*, 2023). Stocking density and resting comfort are no less important. Overcrowding in pens may restrict subordinate animals' access to the feed trough and comfortable resting areas, leading to reduced lying time, increased social competition and impaired welfare (EFSA AHAW Panel (EFSA Panel on Animal Health and Animal Welfare) *et al.*, 2023). Inadequate resting comfort and prolonged standing may increase the risk of limb lesions, particularly lameness. Lameness, in turn, is associated with pain and behavioural changes, which may be accompanied by a reduction in oestrus behaviour and impaired reproductive performance in the postpartum period (Magrin *et al.*, 2023; Proudfoot, 2023).

Postpartum disorders, including retained placenta, metritis, endometritis and other reproductive disorders, develop as a result of the complex interplay of immune dysfunction, metabolic stress, systemic inflammation and factors relating to the management of the transition period (Várhidi *et al.*, 2024). Thus, modern preventive strategies are based not only on timely pharmacological intervention, but primarily on optimising feeding, housing conditions, animal comfort and management during the critical period around calving (Figueiredo, 2024). An important component of prevention is ensuring proper birthing hygiene, as clean, dry and comfortable birthing pens with adequate sanitary conditions help to reduce bacterial contamination of the genital tract during and after calving, limit the risk of ascending uterine infection and may reduce the likelihood of developing postpartum diseases, in particular metritis (Chirivi & Contreras, 2024; Çömlekcioglu *et al.*, 2024; Várhidi *et al.*, 2024). Equally important is ensuring an adequate level of exercise and physical activity during the postpartum period. Comfortable housing conditions and the ability to move freely promote normal behavioural and physiological adaptation in cows after calving, whilst restricting physical activity may adversely affect their general condition and the course of the postpartum period (Henao-Gonzalez *et al.*, 2023). Timely diagnosis of metabolic disorders and optimisation of the diet are also of great importance. Monitoring the concentrations of β -hydroxybutyrate and calcium in blood serum during the first 24 hours after calving enables the timely detection of subclinical ketosis and hypocalcaemia and the implementation of appropriate corrective measures. Both conditions are associated with an increased risk of postpartum disorders and

may adversely affect uterine contractility, the course of uterine involution, the restoration of the oestrous cycle, and the subsequent reproductive performance of cows. Thus, high-quality technical management and the humane treatment of animals are fundamental prerequisites for maintaining reproductive health, minimising postpartum pathologies and ensuring an adequate level of welfare.

A conceptual model for integrating reproduction into a sustainable livestock farming system

The modern development of the agricultural sector is oriented towards the implementation of sustainable agriculture principles, which involves a balanced combination of economic efficiency, environmental responsibility and social sustainability. In livestock production, an important component of the social dimension of this concept is ensuring high standards of animal welfare, which are increasingly regarded as an integral element of sustainable production systems (Hargreaves-Méndez & Hötzel, 2023; Schoor *et al.*, 2023). For a long time, reproductive performance was viewed exclusively through the prism of economic productivity – reducing the time between calving and successful insemination, and increasing the number of offspring per cow (Fedak *et al.*, 2023). However, in the conceptual model of sustainable development, reproductive function acts as a system-defining element that integrates the biological integrity of the organism, society's ethical requirements and the long-term profitability of the sector.

The decline in reproductive capacity of high-yielding dairy cows under intensive production conditions is regarded as one of the most sensitive manifestations of the overload on the organism's physiological and adaptive mechanisms (Nielsen *et al.*, 2023; Rhoads, 2023). The combination of a high metabolic load, a negative energy balance, stress factors and postpartum adaptation limits the animal's adaptive reserves, manifesting as impaired reproductive function, increased morbidity and reduced welfare (Proudfoot, 2023). Although modern programmes for hormonal synchronisation of the oestrous cycle are an effective tool for reproductive management, their use without concurrent adjustments to feeding, housing conditions, transition period management, and the elimination of causes of metabolic and inflammatory stress does not ensure a sustainable improvement in reproductive performance and does not prevent an increased risk of infertility and premature culling of females (Sorathiya, 2024).

The modern concept of sustainable livestock farming regards productive longevity as one of the key

integrated indicators of production efficiency. Achieving this is based on maintaining a high level of animal health and welfare, which ensures the normal functioning of physiological mechanisms of adaptation and reproduction and creates the conditions for the fuller realisation of reproductive potential. Reducing forced culling by providing a comfortable environment, optimising management and minimising technological and metabolic stress helps to lower the risk of chronic diseases, in particular mastitis, lameness and postpartum disorders, improves the recovery of reproductive function after calving and, consequently, extends the productive lifespan of animals (EFSA AHAW Panel (EFSA Panel on Animal Health and Animal Welfare) *et al.*, 2023; Thomsen *et al.*, 2023). Extending productive life also reduces the need to rear replacement young stock, as a lower rate of cow replacement reduces the need for replacement animals and the associated costs. Modelling of dairy production systems shows that improving reproductive efficiency and, consequently, reducing the need to replace cows contributes to a simultaneous increase in productive longevity and the economic and environmental efficiency of production (Winter *et al.*, 2024). Thus, a reduction in forced culling and the need for herd replacement are interrelated mechanisms through which improvements in health, welfare and reproductive efficiency translate into increased economic efficiency and sustainability in livestock farming.

Reproductive health and a high level of animal welfare are key factors in the environmental sustainability of modern livestock farming. Improving fertility, reducing morbidity and increasing productive longevity contribute to a more efficient use of resources, a reduced need for replacement stock and lower greenhouse gas emissions per unit of production, which is of particular importance in the context of global climate change (Diavão *et al.*, 2023; Astuti *et al.*, 2024). An important aspect in this context is the reduction of the greenhouse gas footprint of livestock farming. A decline in reproductive efficiency – in particular, a longer period from calving to successful insemination, an increase in the calving interval and the duration of non-productive days – reduces the efficiency of feed utilisation and increases the intensity of greenhouse gas emissions per unit of output. Conversely, optimising reproduction through improvements in animal welfare, health and management promotes more efficient feed-to-product conversion and reduces the environmental footprint of production. Equally important is the economic and financial sustainability of production. Growing public demand for ethically produced livestock products is making animal welfare a key factor

in market competitiveness (Schütz *et al.*, 2023). A focus on disease prevention, high welfare standards, proper management and humane treatment helps to reduce the need for medicinal interventions, boosts consumer confidence, adds value to products and strengthens the producer's reputation.

Integrating reproductive indicators into the animal welfare assessment system requires a shift from a reactive model, focused primarily on treating individual postpartum and reproductive pathologies, to proactive, preventative management (LeBlanc, 2023; Pascottini *et al.*, 2023). In the concept of sustainable livestock farming, priority is given to the early detection of risk factors, the optimisation of feeding, housing conditions, biosecurity and welfare, and the systematic monitoring of herd health, which makes it possible to prevent the development of reproductive disorders even before clinical signs appear (Ramakant *et al.*, 2023). This model comprises three key levels: The first is the basic level (environment and management). Consistent adherence to animal hygiene requirements, a balanced diet, comfortable housing conditions, sufficient space for the animals, prevention of overcrowding in pens and positive staff-animal interactions are key components of modern welfare management. Together, these measures help to maintain the animals' health, normal behaviour, reproductive function and long-term productivity (Nielsen *et al.*, 2023; Sorathiya, 2024).

The second is the diagnostic and monitoring level (digitalisation). Systematic, automated monitoring of behavioural indicators (rumination, physical activity, lying and resting times), combined with the assessment of biochemical markers of metabolic and oxidative stress, enables the early detection of health and welfare issues even before the development of pronounced clinical signs (Tufarelli *et al.*, 2023). This approach is a key component of modern precision livestock farming and enables timely adjustments to management and preventative measures (Mirzaei *et al.*, 2023). The third is the physiological level (reproduction optimisation). A high level of animal welfare, ensured by optimal housing conditions, a balanced diet and the minimisation of stress, creates the physiological conditions for the timely restoration of post-partum oestrus cycles, the preservation of females' reproductive potential, improved conception rates and reduced early embryonic mortality (Denicol & Siqueira, 2023; Diavão *et al.*, 2023). The proposed model is structural and logical in nature and describes the directional relationships between technological and environmental factors, the physiological adaptive response, behavioural reactions, reproductive indicators and the overall state of animal welfare (Fig. 3).

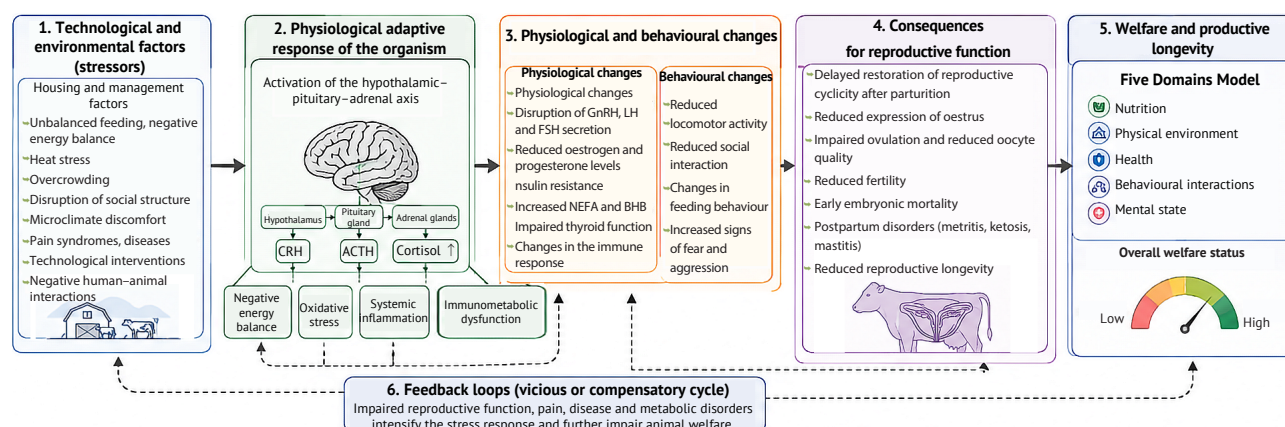


Figure 3. Conceptual model of the relationship between technological stress, physiological indicators and reproductive function within the animal welfare system

Source: developed by the authors

Unlike a set of recommendations, the model defines a sequence of interrelated levels and indicators through which housing conditions and environmental

stressors are transformed into physiological and behavioural changes, and subsequently into reproductive dysfunction and changes in welfare (Fig. 4).

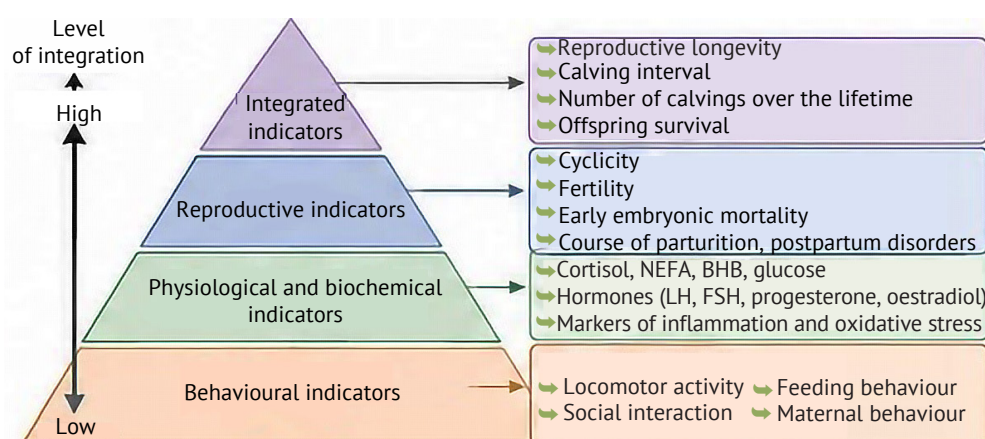


Figure 4. Multilevel welfare indicators through the lens of reproductive function

Source: developed by the authors

A particular place in this system is occupied by cortisol concentration as a biomarker of the physiological response to stress. However, cortisol is not regarded as an independent determinant of welfare but is interpreted in conjunction with behavioural, physiological, biochemical and reproductive indicators. This approach provides a multiparametric assessment of welfare and establishes the rationale for moving from the monitoring of individual indicators towards an integrated assessment of animal condition. Thus, reproductive health is not merely one of many production characteristics but a key integrated marker of the biological harmony between the animal and the human-designed technological environment. Without ensuring an adequate level of welfare and minimising stress load,

genuinely sustainable development of livestock production cannot be achieved.

The proposed conceptual model considers the reproductive health of farm animals not as an isolated outcome of the reproductive system's functioning, but as an integrated indicator shaped by physiological condition, housing conditions, technological factors, behaviour, stress levels and the animals' overall welfare. This approach is consistent with the modern understanding of welfare as a complex state of the animal, shaped by the interaction of its physiological capabilities, behaviour and environmental conditions. One of the key tenets of the proposed model is the interrelationship between environmental conditions, physiological response and reproductive outcomes. Heat stress is

a prime example of such a multi-level effect. A study by B. Stefanska *et al.* (2024) showed that heat stress in the period immediately prior to calving is associated with subsequent changes in productivity, fertility and the immunometabolic status of dairy cows. This supports the proposition of the proposed model that adverse environmental influences can have delayed consequences for reproductive function, manifesting themselves even after the immediate period of stress has ended.

It is also important to note that environmental influences can manifest directly at the level of reproductive cells. Thus, husbandry practices can influence reproductive health not only through general indicators of productivity or physiological status, but also directly through the conditions under which the reproductive system functions. P. Skliarov *et al.* (2026) reviewed current approaches to the prevention of nutritional infertility in cows and heifers. The study systematises the importance of a complete and balanced diet, ensuring animals receive the necessary macro- and micro-nutrients, monitoring vitamin and mineral status, and taking the animals' physiological condition into account when formulating rations. The authors concluded that the prevention of nutritional infertility should be based on systematic and continuous monitoring of the metabolic support for reproductive function.

Another important component of the proposed model is animal behaviour. Behavioural changes may reflect functional disturbances, stress and adaptive responses even before the appearance of pronounced clinical signs. In this context, behavioural indicators should be considered not only as independent measures of welfare, but also as potential intermediary links between housing conditions, physiological status and reproductive outcomes. This approach is consistent with the principle that welfare should be assessed based on a combination of complementary indicators, rather than a single parameter. This takes on particular significance in light of the development of precision livestock farming technologies. Automated monitoring enables information on the behavioural and physiological characteristics of animals to be obtained on a near-continuous basis. At the same time, digital technologies should be regarded as a tool to complement, rather than replace, clinical and veterinary assessment. Their value lies in the ability to detect deviations from individual norms in a timely manner and to combine the signals obtained with other indicators of the animal's condition. A contemporary analysis of the possibilities offered by precision livestock farming also highlights the potential of digital technologies for monitoring health and welfare, whilst at the same time drawing attention to the need to take into account the ethical, technological and

environmental aspects of their application (Papakonstantinou *et al.*, 2024).

A. Pavlenko *et al.* (2023) investigated changes in the behaviour, health and productivity of dairy cows following the transition from tethered to loose housing. The authors assessed the animals' adaptation to the new housing system and compared behavioural and production indicators before and after the change in conditions. It was found that the transition to loose housing was accompanied by changes in the cows' behaviour, health indicators and productivity. The results confirmed that a change in the housing system significantly affects the biological and behavioural characteristics of the animals and should therefore be taken into account when assessing their welfare.

M. Pons *et al.* (2025) investigated the effect of different housing conditions on behavioural and biochemical indicators of welfare in dairy cows in mixed feeding systems. The authors compared cows housed in compost barns with animals kept in open-air housing on a soil surface. It was found that the type of housing influenced a number of behavioural indicators, in particular the duration of lying down, standing, walking and rumination, as well as the concentration of total protein and globulins in the blood. The results confirmed that housing type is an important factor that must be taken into account in a comprehensive assessment of dairy cows' welfare. H. Marina *et al.* (2024) investigated the factors determining social interactions among dairy cows, using data on the spatial location of the animals and social network analysis. The authors assessed how the individual characteristics of cows and their housing conditions influence the formation and maintenance of social bonds within the herd. It was found that social interactions between cows are not random but are shaped by individual and group factors. The authors concluded that the analysis of social behaviour could be a promising tool for assessing the social environment and welfare of dairy cows.

J. Thompson *et al.* (2022) conducted a long-term randomised study to assess the impact of increased living space on the behaviour, productivity and reproductive performance of dairy cows. In the study, 150 Holstein cows were housed for one year under two different space allocation levels – 3 and 6.5 m² of living space per animal. It was found that increased space led to longer lying and rumination times and higher milk yield, but was accompanied by a longer time to conception following calving. The authors concluded that housing conditions can simultaneously influence behavioural, productive and reproductive characteristics in different ways, which highlights the need to take them into account comprehensively when assessing animal welfare and the sustainability of dairy production.

An important mechanism linking the physiological, behavioural and reproductive components of the proposed model is the stress response. Stress can alter the neuroendocrine regulation of reproductive function and affect reproduction through a complex of interrelated physiological mechanisms (Wrzecińska *et al.*, 2021). At the same time, reproductive disorders should not automatically be interpreted as a direct consequence of a single specific stressor. They may result from the cumulative impact of adverse environmental conditions, metabolic stress, diseases, management failures and the organism's inability to adapt. In this context, reproductive health should be regarded as an indicator of the long-term outcome of the interaction of many factors. Unlike an isolated physiological or behavioural indicator, reproductive function integrates the effects of environmental factors and management practices over an extended period. At the same time, its informative value depends on the specific species, age, physiological state, productivity and the husbandry system employed.

The proposed model is also consistent with the modern approach to assessing positive welfare. Alongside the detection of diseases, stress or other negative states, it is necessary to take into account the animals' ability to fulfil their behavioural needs and develop positive states. Accordingly, reproductive health can be regarded as one component of a comprehensive assessment system, but not as a substitute for other welfare indicators. Approaches to defining and assessing animal welfare emphasise the need to use complementary indicators and to draw a clear distinction between indicators of health, behaviour and general welfare (Papageorgiou & Simitzis, 2022).

An important aspect of the proposed model is also the assessment of the implications of digital monitoring for management decision-making. The mere acquisition

of large amounts of data does not guarantee an improvement in animal welfare. Appropriate selection of indicators, determination of threshold values and correct interpretation of the information obtained are essential. F. Edwardes *et al.* (2024) showed that the choice of a classification model for the automated detection of suboptimal mobility may involve a trade-off between economic and welfare outcomes. This is directly relevant to the proposed concept, as a monitoring system should be oriented not only towards production efficiency but also towards the timely detection of conditions that may adversely affect animal health, welfare and, ultimately, reproductive function.

Further support for an integrated approach is provided by the findings of H. Neave *et al.* (2024), who demonstrated an association between the social context of cow-calf interactions, maternal behaviour and oxytocin concentration. The authors also noted that the hormonal response depended on the strength of the bond between the dam and her offspring. This demonstrates that behavioural and social interactions may be associated with physiological processes relevant to animal welfare. At the same time, such relationships need to be interpreted comprehensively, as no single behavioural or hormonal indicator can independently characterise overall welfare status. Thus, the results of the literature analysis support the proposed conceptual model, in which the technological environment, physiological and metabolic status, behaviour, stress and reproductive function are regarded as interconnected components of a single system. A fundamental feature of the proposed approach is the consideration of reproductive function not as an isolated production indicator but as one of the integrated outcomes of an animal's adaptation to housing conditions, management practices and the surrounding environment (Fig. 5).

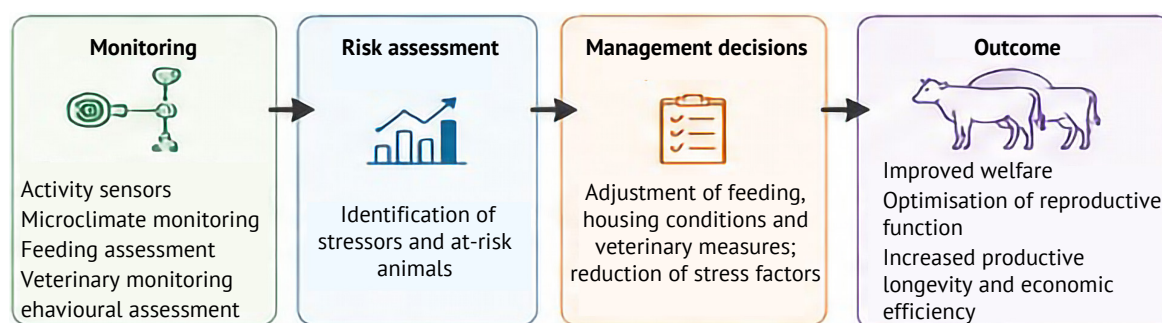


Figure 5. Practical application of the model in management

Source: developed by the authors

At the same time, reproductive function cannot be regarded as a universal, standalone indicator of welfare. High fertility does not necessarily indicate optimal

welfare, just as an isolated reproductive disorder is not always a direct consequence of inadequate housing conditions. Thus, the practical application of the

proposed model involves a comprehensive assessment of reproductive, clinical, physiological, behavioural and environmental indicators. Overall, the proposed model can be used as a conceptual basis for the further development of reproductive welfare monitoring systems. Its practical significance lies in the ability to combine traditional veterinary assessment methods with behavioural, physiological and digital indicators, which will enable a shift from reactive detection of reproductive problems to their early prediction and prevention. In this approach, reproductive health is viewed as a long-term, integrated outcome of the interaction between the environment, management, health, stress, behaviour and the animal's adaptive capacity.

CONCLUSIONS

Activation of the hypothalamic-pituitary-adrenal axis in response to chronic and environmental stress is accompanied by systemic hypercortisolaemia, which leads to direct suppression of the gonadotropic axis at the hypothalamic, pituitary and ovarian levels. This process is exacerbated by metabolic distress, oxidative damage to oocytes and systemic endotoxaemia (LPS-induced translocation), which collectively cause anovulation, anaphrodisia, increased embryonic mortality and the creation of transgenerational epigenetic risks for the offspring. Assessing reproductive function through the lens of the Five Domains model confirms its significance as one of the sensitive biological indicators of an animal's psycho-emotional and locomotor state. Disruptions in the domains of nutrition, the physical environment, health and behavioural autonomy translate into negative mental states (anxiety, pain, exhaustion), which may act as a biological trigger for the suppression of the oestrous cycle and the manifestation of silent oestrus.

Interaction between the mother and her offspring is an important factor in the behavioural and physiological adaptation of animals; however, its impact on welfare depends on the form, duration and conditions under which contact takes place. Different housing

systems and methods of separating mothers from their offspring can have both positive and undesirable consequences for the animals' health, behaviour and adaptation; thus, no single form of contact can be considered universally optimal without taking specific operational conditions into account. The proposed conceptual model is based primarily on evidence from the dairy cattle sector, where the interrelationships between housing conditions, stress, physiological and behavioural responses, reproductive function and welfare have been studied most comprehensively. At the same time, its structural and logical framework is based on general biological principles, which creates the conditions for adaptation to other species and livestock systems. Such interspecies extrapolation is conceptual in nature and requires separate empirical verification.

Prospects for further research lie in the experimental validation of the proposed conceptual model and the identification of quantitative relationships between indicators of welfare, stress, physiological status, behaviour and reproductive function. Of particular promise is the development of integrated systems for the early prediction of reproductive disorders based on a combination of clinical, hormonal, metabolic, behavioural and digital indicators. Further research should also identify specific threshold values and validated combinations of indicators for different species and production systems, as well as evaluate the effectiveness of such systems in long-term field studies. This will enable a transition from a conceptual model to a practically validated tool for monitoring reproductive welfare and supporting management decisions in sustainable livestock farming.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

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Відтворення як ключова складова добробуту тварин: концептуальні основи для сталого тваринництва

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Анотація. Сучасне глобальне тваринництво перебуває під впливом трансформаційних змін, зумовлених необхідністю впровадження концепцій сталого розвитку, етичного господарювання та високих стандартів добробуту тварин. Тривалий час у зоотехнічній науці та практиці репродуктивні показники оцінювалися переважно крізь призму економічної ефективності та інтенсифікації виробництва, тоді як їхнє значення як одного з показників біологічного, фізіологічного та психоемоційного стану тварин залишалося недостатньо розкритим. Метою дослідження було теоретичне обґрунтування та розробка цілісної концептуальної моделі відтворення як ключової складової добробуту сільськогосподарських тварин для забезпечення довгострокової стійкості тваринницької галузі. Методологія роботи базувалася на застосуванні системно-структурного аналізу, наукового узагальнення, порівняння та концептуального моделювання результатів сучасних фундаментальних і прикладних досліджень, індексованих у наукометричних базах даних Scopus та Web of Science. У результаті дослідження деталізовано нейроендокринні та фізіологічні механізми пригнічення репродуктивної функції під впливом технологічного та середовищного стресу, викликаного активацією гіпоталамо-гіпофізарно-надниркової осі та підвищенням рівня кортизолу. Встановлено причинно-наслідкові зв'язки між порушеннями умов утримання, хронічним стресом та затримкою відновлення статевих циклічності після родів. Обґрунтовано значення реалізації природної репродуктивної та материнської поведінки як важливого індикатора формування позитивного емоційного стану тварин у контексті сучасної моделі «П'яти доменів». Сформовано концептуальну рамку, що інтегрує параметри репродуктивного здоров'я, поведінкові реакції та технологічні чинники у єдину систему оцінки добробуту. Практичне значення одержаних результатів полягає у розробці науково обґрунтованих підходів до адаптації технологічних процесів у тваринництві, що дає змогу ефективно поєднати високий рівень добробуту тварин із їхньою відтворною здатністю та довгостроковою економічною ефективністю господарювання.

Ключові слова: репродуктивне здоров'я; модель п'яти доменів; технологічний стрес; материнська поведінка; фізіологічна стійкість