STM JOURNALS

Research & Reviews: Journal of
Veterinary Science and Technology

ISSN: 2319-3441 (Online)
ISSN: 2349-3690 (Print)
Volume 15, Issue 2, 2026
May–August
DOI (Journal): 10.37591/RRJOVST

https://journals.stmjournals.com/rrjovst

Review RRJOVST

Reproductive Challenges in Tropical Dairy Cows: Exploring Stressors and Mitigation Strategies for Sustainable Development

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Abstract

Reproductive efficiency in tropical dairy cows is often compromised by a range of environmental, nutritional, and management-related stressors. These stressors, including heat, humidity, poor-quality feed, disease, and parasitic infestations, significantly affect fertility, leading to prolonged calving intervals, reduced conception rates, and increased reproductive disorders. Heat stress, in particular, has been identified as a primary factor influencing reproductive performance by disrupting hormonal balance, reducing feed intake, and impairing overall cow health. Additionally, nutritional deficiencies, such as imbalances in protein, energy, and essential micronutrients, exacerbate metabolic disorders that further compromise fertility. Infectious diseases and parasitic infestations further complicate the situation, reducing immune function and increasing susceptibility to reproductive disorders. This study explores the various stressors that hinder reproductive efficiency in tropical dairy cows and presents practical mitigation strategies for addressing these challenges. The paper discusses the importance of heat abatement measures, optimal nutrition strategies, and effective disease and parasite management in enhancing fertility. Additionally, the role of genetic selection for heat tolerance and reproductive traits, alongside advancements in management practices, is examined as part of a sustainable approach to improving reproductive outcomes. By focusing on integrated management solutions, this study aims to provide insights into improving the reproductive performance of dairy cows in tropical regions, ensuring both animal welfare and farm productivity in the face of ongoing climate change.

Keywords: Climate change, dairy cow fertility, heat stress, nutritional stress, reproductive disorders, sustainable development, tropical dairy farming

INTRODUCTION

Reproductive efficiency is a cornerstone of successful dairy farming, particularly in tropical regions where environmental and management factors significantly impact fertility [1]. Tropical dairy cows are subject to a variety of stressors, including high temperatures, humidity, and seasonal variations, all of which can disrupt their reproductive cycles [2]. Heat stress, one of the most prominent challenges, has been shown to negatively affect hormonal regulation, feed intake, and overall health, leading to a decrease in reproductive performance [3]. In addition to thermal stress, nutritional deficiencies and imbalances in essential nutrients, such as proteins, minerals, and vitamins further contribute to reproductive inefficiencies. Diseases and parasitic infestations in tropical climates exacerbate these issues, reducing the overall health and fertility of dairy cows, leading to delayed calving intervals and increased reproductive disorders [4].

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Received Date: October 21, 2025
Accepted Date: December 01, 2025
Published Date: December 02, 2025

Citation: Md. Emran Hossain, Shilpi Islam. Reproductive Challenges in Tropical Dairy Cows: Exploring Stressors and Mitigation Strategies for Sustainable Development. Research & Reviews: Journal of Veterinary Science and Technology. 2026; 15(2): 7–26p.

Understanding the complex interactions between these stressors is crucial to developing effective mitigation strategies [5]. Traditional management practices often fall short in addressing the multifaceted nature of reproductive challenges faced by tropical dairy farmers. Heat abatement, optimal nutritional management, and disease control are essential for improving reproductive outcomes [6]. However, tropical dairy farming must also adapt to the challenges posed by climate change, which is intensifying the frequency and severity of extreme weather conditions, including prolonged heatwaves and altered rainfall patterns [7]. Therefore, a comprehensive approach that incorporates these environmental, nutritional, and management factors is necessary to enhance reproductive efficiency in tropical dairy systems.

This study presents a novel approach to addressing reproductive challenges in tropical dairy cows by integrating various stressors into a cohesive framework. Unlike previous studies that focus on individual stress factors, this study takes a holistic view of the interrelated impacts of thermal, nutritional, and infectious stressors. It further emphasizes the importance of sustainable development through the adoption of innovative management practices, including genetic selection for heat tolerance, advanced nutritional strategies, and improved health management. By addressing the combined challenges faced by tropical dairy cows, this study provides a comprehensive guide for enhancing reproductive performance while promoting the long-term sustainability of dairy farming in tropical regions.

THERMAL STRESS

Heat Stress

Heat stress mitigation involves the implementation of heat abatement systems, such as evaporative cooling, water spraying, and foggers, which help reduce body temperature. Nutritional strategies, including the provision of electrolyte supplements, can aid in balancing fluids lost due to sweating [8]. Additionally, adjusting calving patterns and offering nutritional support during high-heat periods can help maintain reproductive performance and milk production while promoting sustainable dairy farming practices.

Humidity Stress

To mitigate humidity stress, improving airflow within barns or shelters can significantly reduce the adverse effects of high humidity on cows. Managing stocking density and ensuring cows have access to cool, shaded areas can enhance thermoregulation [6, 9, 10]. Further, providing dietary adjustments that help improve heat tolerance, such as increasing the intake of fiber and essential nutrients, can help cows adapt to humid conditions and improve reproductive outcomes.

Seasonal Temperature Fluctuations

Mitigating seasonal temperature fluctuations requires effective climate control in housing systems and the use of heat stress management tools [11]. Seasonal adjustments in feeding schedules, along with offering higher energy diets during extreme weather conditions, can help mitigate temperature-related reproductive challenges. Additionally, farmers can adopt long-term strategies, such as diversifying farm locations and implementing climate-smart practices to buffer seasonal extremes and maintain reproductive efficiency.

Solar Radiation Exposure

Reducing solar radiation exposure can be achieved by providing adequate shelter, such as roofs or trees, to protect cows from direct sunlight [12]. Implementing artificial shade structures or using reflective materials to reduce heat absorption in the barn can also help mitigate the effects of solar radiation. Furthermore, using lighter-colored equipment or barn walls that reflect sunlight can prevent excessive heating, maintaining cow comfort and reproductive health.

Reduced Thermoregulatory Capacity

Cows with lower heat tolerance can benefit from genetic selection focused on heat-resilient traits [13]. Additionally, modifying farm environments by using cooling systems and proper ventilation

ensures that animals can maintain a comfortable body temperature. Incorporating these approaches into breeding programs and farming practices ensures cows can cope with environmental stressors, improving reproductive outcomes and contributing to sustainable dairy farming practices in tropical climates.

Heat Shock Protein Activation

Strategies to mitigate the activation of heat shock proteins include the use of antioxidant-rich diets that reduce oxidative stress in cows [14]. Reducing heat exposure through shade, cooling systems, and appropriate housing can prevent the prolonged activation of heat shock proteins, improving reproductive health. Further, managing stress levels through careful farm management, reduced transportation, and improving overall cow comfort helps minimize the metabolic disruptions caused by heat stress.

Increased Sweating Leading to Dehydration

Ensuring a consistent and abundant water supply is a primary strategy for mitigating dehydration due to excessive sweating [4]. Providing salt licks and electrolytes helps replenish lost minerals and maintain hydration. Additionally, improving cooling methods, such as misters and fans, can reduce excessive sweating and help regulate body temperature. These measures, when combined with proper nutrition and a controlled farm environment, promote reproductive health and overall cow welfare.

Elevated Rectal Temperature

Elevated rectal temperatures can be mitigated by monitoring cows' body temperature regularly and implementing cooling strategies, such as water misting or the installation of fans [15]. Providing high-quality feed with adequate fiber can reduce stress and improve thermoregulation. Additionally, incorporating better heat management systems during hot weather and adjusting milking schedules to cooler parts of the day can further reduce heat exposure, allowing cows to maintain better reproductive health.

Disrupted Endocrine Functions

To address the disruption of endocrine functions, farmers can focus on nutrition and management practices that support hormonal balance. Supplementing with minerals like magnesium and calcium can help stabilize the endocrine system [16]. Additionally, introducing cooling systems and modifying feeding routines to avoid feeding during the hottest parts of the day can support the normal functioning of reproductive hormones. Ensuring cows' comfort through shade, water, and adequate space also helps maintain endocrine health.

Poor Feed Intake Due to Heat

Mitigating reduced feed intake during heat stress involves providing cool, fresh, and palatable feed. Offering high-quality forage and using high-energy, easily digestible feed types can help compensate for reduced intake [17]. Moreover, feeding cows during cooler times of the day, such as early morning or evening, minimizes the impact of heat stress on digestion. These strategies contribute to better nutritional intake, ensuring cows remain healthy and maintain reproductive performance, leading to sustainable dairy farming practices.

NUTRITIONAL STRESS

Seasonal Feed Scarcity

Seasonal feed scarcity is a significant challenge in tropical dairy farming, where dry seasons can limit the availability of high-quality feed. During such periods, the lack of fresh forage affects the cows' overall nutrition and reproductive performance [18]. Mitigation strategies include preserving forage during abundant seasons for use in leaner periods, using silage and hay, and supplementing with concentrates to ensure that cows receive adequate nutrition year-round, promoting sustainable reproductive efficiency.

Low-Quality Roughage Availability

Low-quality roughage availability reduces the intake of essential nutrients and negatively impacts rumen function in dairy cows. Poor-quality forages are often low in fiber and digestibility, leading to inadequate nutrient absorption [19]. Strategies to mitigate this include supplementing roughage with concentrates, improving pasture management, and using higher-quality roughage alternatives, such as legumes, to support cow nutrition and reproductive health, ensuring long-term sustainability.

Protein Deficiency

Protein deficiency is a critical factor affecting the reproductive performance of dairy cows. Insufficient protein intake can lead to poor body condition, delayed estrus, and impaired conception [20]. To mitigate protein deficiency, providing high-protein feeds, such as oilseeds, legumes, and protein supplements, is essential. Balancing protein levels with energy intake is also crucial to maintaining optimal health and reproductive performance in dairy cows, contributing to sustainable production practices.

Energy Imbalance

Energy imbalance occurs when cows do not consume enough energy to meet their physiological demands, often due to low-quality feed or high-energy requirements during lactation [21]. This imbalance can lead to reduced fertility, lower milk production, and metabolic disorders. To address this, providing energy-dense feeds, including grains and high-quality concentrates, during lactation and adjusting feeding strategies to match cows' energy needs can improve reproductive health and contribute to sustainable dairy farming.

Mineral Imbalances

Mineral imbalances, particularly deficiencies in calcium (Ca), phosphorus (P), magnesium (Mg), zinc (Zn), and selenium (Se), can severely affect reproductive efficiency. These minerals play key roles in hormone regulation, immune function, and bone health. Supplementing mineral-rich feeds, using mineral salts, and improving pasture management can help address these imbalances [11]. Ensuring proper mineral supplementation during periods of high reproductive demand promotes optimal fertility and sustainability in dairy production.

Vitamin A, D, and E Deficiency

Deficiencies in vitamins A, D, and E impact dairy cows' immune system, fertility, and overall health. Vitamin A is crucial for reproductive hormone production, while vitamin D is essential for calcium metabolism, and vitamin E acts as an antioxidant. Mitigating these deficiencies involves supplementing the diet with vitamin-rich feeds, including green forages, oilseeds, and vitamin additives, ensuring cows maintain optimal reproductive health and long-term productivity [22].

Mycotoxin Contamination in Feed

Mycotoxin contamination in feed is a serious concern in tropical regions, where high humidity and poor storage conditions favor fungal growth in forages and grains. These toxins can damage liver function, impair fertility, and cause health problems. Mitigation strategies include proper feed storage, using mycotoxin binders in the diet, and ensuring that cows receive high-quality, uncontaminated feed to reduce reproductive challenges and ensure sustainable dairy farming practices [22].

Deficiency of Essential Fatty Acids

Deficiency of essential fatty acids (EFAs) can affect dairy cows' fertility by impairing reproductive hormone production, egg quality, and embryo development. Including high-quality fat sources like linseed, canola, and fish oil in the diet helps address EFA deficiencies. Providing balanced fat supplementation ensures cows' optimal reproductive function and health, contributing to improved fertility rates and sustainable dairy farming practices.

Excessive Fiber Reducing Digestibility

Excessive fiber in the diet can reduce digestibility and prevent adequate nutrient absorption, leading to lower energy intake and poor reproductive health. To mitigate this, adjusting fiber content to match the cows' digestive capacity and supplementing with concentrates or easily digestible forages can enhance nutrient utilization. Properly balancing fiber and concentrate in the diet ensures efficient digestion, improves reproductive outcomes, and supports sustainable dairy farming [22].

Unbalanced Dietary Cation-Anion Balance

An unbalanced dietary cation-anion balance (DCAB) can affect calcium metabolism, leading to disorders, such as hypocalcemia, which negatively impacts reproductive efficiency. Managing DCAB by balancing the intake of cations (Na, K) and anions (Cl, S) in the diet can help regulate acid-base status, improve calcium absorption, and support reproductive function. Using appropriate mineral supplements and adjusting the dietary formulation based on the cow's physiological stage can mitigate reproductive challenges and promote sustainability in tropical dairy farming [23–26].

INFECTIOUS DISEASES

Mastitis

Mastitis, an infection of the udder, is one of the most common and economically damaging diseases in dairy cows. It impairs milk production and quality, leading to financial losses. Prevention includes maintaining proper milking hygiene, using effective sanitizing protocols, and ensuring proper milking machine maintenance. Additionally, providing adequate nutrition to support immune function and managing cow comfort can help reduce the incidence of mastitis, improving both milk yield and reproductive efficiency, thus contributing to sustainable farming [27].

Endometritis

Endometritis, an inflammation of the uterus, is a significant cause of infertility in dairy cows. It is often caused by bacterial infections during calving or postpartum. Effective management includes maintaining clean calving areas, prompt treatment of affected cows with antibiotics, and improving reproductive management practices. Additionally, ensuring good nutrition, especially postpartum, can help the cow's immune system combat infections, thereby improve reproductive performance and contributing to the overall sustainability of dairy farming [21].

Metritis

Metritis, an infection of the uterine lining, can lead to severe reproductive failure if left untreated. The condition is often associated with bacterial infections following calving. Early detection and treatment with appropriate antibiotics are essential [28]. Preventive measures include maintaining clean calving environments and minimizing stress. Improving postpartum nutrition and health management can support immune function, prevent metritis, and ensure cows return to reproductive cycles quickly, promoting sustainable dairy production.

Brucellosis

Brucellosis is a zoonotic disease caused by Brucella bacteria, leading to abortion, reduced milk yield, and infertility in dairy cows. Controlling brucellosis involves regular testing, vaccination, and isolating infected animals to prevent spread. Biosecurity measures, including preventing contact with wildlife and using strict herd management protocols, are key. Effective vaccination programs and maintaining herd health can significantly reduce the risk of brucellosis, enhance reproductive performance and supporting sustainable dairy farming practices [29].

Leptospirosis

Leptospirosis is a bacterial infection transmitted through contaminated water, soil, or urine from infected animals. It can lead to abortion, reduced milk production, and fertility problems. To mitigate leptospirosis, farmers should implement strict biosecurity measures, such as controlling water sources and maintaining proper sanitation [25]. Vaccination programs and prompt treatment of infected animals

can help reduce the incidence of leptospirosis and prevent its impact on reproductive health, promoting the long-term sustainability of dairy farming.

Bovine Viral Diarrhea

BVD is a viral disease that can cause reproductive failure, immunosuppression, and fetal abnormalities. It is primarily transmitted through contact with infected animals. Effective control includes vaccination, testing for persistently infected animals, and eliminating infected individuals from the herd [30]. Maintaining biosecurity measures and preventing contact with other potentially infected livestock can help reduce the prevalence of BVD, ensuring improved reproductive outcomes and contributing to more sustainable and disease-free dairy farming.

Infectious Bovine Rhinotracheitis

IBR, caused by the herpesvirus, leads to respiratory problems, reproductive failures, and economic losses. The virus can cause abortion, reduced fertility, and increased susceptibility to other infections. Preventive measures include vaccination, maintaining strict biosecurity, and testing for IBR in new herd additions [31]. Ensuring herd immunity through vaccination and good health management practices can help reduce the impact of IBR, ultimately supporting reproductive health and sustainability in tropical dairy farming.

Trypanosomiasis

Trypanosomiasis, transmitted by tsetse flies, is a major concern in tropical regions. It causes infertility, reduced milk yield, and overall poor health in dairy cows. Control measures include the use of insecticides, strategic use of trypanocidal drugs, and managing grazing patterns to avoid areas with high tsetse fly populations [27]. By addressing trypanosomiasis, dairy farmers can improve cow health, reduce reproductive problems, and enhance farm sustainability.

Campylobacteriosis

Campylobacteriosis, caused by Campylobacter bacteria, leads to infertility and early embryonic death in dairy cows. The disease is primarily spread through fecal-oral transmission. Proper manure management, ensuring clean water sources, and isolating infected animals are key strategies for prevention [29]. Maintaining herd health with regular veterinary checks and vaccinations can reduce the risk of campylobacteriosis, leading to improved reproductive efficiency and supporting sustainable dairy production.

Neosporosis

Neosporosis is a parasitic infection that can cause abortion and reduced fertility in dairy cows. It is transmitted through infected feed or contaminated environment. Preventive strategies include controlling feed contamination, isolating infected cows, and ensuring good herd management practices. Additionally, using diagnostic testing and improving biosecurity measures can reduce the risk of Neosporosis, thus maintaining reproductive health and ensuring long-term sustainability of dairy farming [30].

PARASITIC INFESTATIONS

Ticks and Tick-Borne Diseases

Ticks are vectors for a variety of serious diseases like Theileriosis and Anaplasmosis, which significantly affect the reproductive performance of dairy cows. These diseases cause fever, anemia, and reduced fertility [27]. Control strategies include regular tick control through acaricides, pasture management to reduce tick populations, and vaccination programs where applicable. By preventing tick-borne diseases, farmers can enhance cow fertility and reproductive health, leading to more sustainable dairy farming practices.

Internal Parasites

Internal parasites, such as Haemonchus and Ostertagia, cause gastrointestinal issues, anemia, and poor nutrient absorption in dairy cows. These parasitic infestations reduce milk yield and reproductive

efficiency [29]. Managing internal parasites involves deworming protocols, rotational grazing, and improving pasture hygiene to reduce parasite load. Regular veterinary checks and strategic use of anthelmintics can help mitigate parasitic effects on reproductive health, promoting long-term sustainability in dairy farming.

Liver Flukes

Fascioliasis, caused by liver flukes, affects the liver and overall health of dairy cows, leading to reduced milk production and fertility. Liver flukes are commonly contracted through contaminated water sources and grazing in wet areas. To mitigate this, controlling the snails that host liver fluke larvae and using deworming treatments are essential. Ensuring clean water sources and managing pasture environments are key to preventing fascioliasis, which enhances reproductive efficiency and ensures sustainable dairy production [30].

Gastrointestinal Nematodes

Gastrointestinal nematodes are common in tropical dairy cows and lead to reduced feed conversion, lower milk yield, and fertility issues [31]. Effective management includes regular deworming schedules, proper pasture rotation, and the use of anthelmintics. Additionally, maintaining optimal cow nutrition helps support immune function against nematode infestations. By controlling gastrointestinal parasites, dairy farmers can improve reproductive performance and reduce productivity losses, contributing to sustainable dairy farming.

Coccidiosis

Coccidiosis, caused by protozoan parasites, affects the digestive system of dairy cows, leading to diarrhea, poor weight gain, and compromised immune function. In severe cases, coccidiosis can disrupt reproductive cycles. Control strategies include using coccidiostats, maintaining clean and dry living environments, and reducing stress on cows. Effective management of coccidiosis ensures optimal cow health, improves fertility, and supports the overall sustainability of dairy farming [27].

External Parasites

External parasites, such as mites and lice can cause skin irritation, hair loss, and anemia in dairy cows. These parasites also affect milk production and reproductive health. Managing external parasites involves using insecticides, improving cow hygiene, and maintaining clean housing. Regular checks for signs of infestation and quick intervention are key to preventing the negative impact of external parasites on fertility and overall cow health, ensuring sustainability in dairy farming [30].

Trypanosome-Induced Reproductive Failure

Trypanosomiasis, caused by the Trypanosoma parasite, is prevalent in tropical regions and leads to reproductive failure, decreased fertility, and poor overall health in dairy cows. It is transmitted by tsetse flies [29]. Control measures include using trypanocidal drugs, controlling fly populations, and strategic grazing management. Effective management of trypanosomiasis improves reproductive performance and supports sustainable dairy production by preventing infertility and disease spread.

Subclinical Parasitic Infections

Subclinical parasitic infections can silently affect dairy cows' reproductive health, leading to reduced fertility and poor performance without overt symptoms. Regular monitoring for parasite load, periodic deworming, and improved herd management practices are crucial to detecting and managing subclinical infections. Ensuring cows are parasite-free promotes better reproductive efficiency and contributes to the long-term health and productivity of the herd, enhancing sustainable dairy farming [31].

Vector-Borne Disease Transmission

Vector-borne diseases, including those transmitted by flies, mosquitoes, and ticks, significantly impact the reproductive efficiency of dairy cows. These diseases can cause infertility, reduced milk production, and overall cow health issues [27]. Implementing vector control measures, such as

insecticides, fly traps, and maintaining clean environments can reduce transmission. Improving biosecurity practices and providing vaccines where applicable help to mitigate vector-borne diseases, leading to enhanced reproductive health and more sustainable dairy farming practices.

Helminth-Induced Immune Suppression

Helminth infestations can suppress the immune system of dairy cows, leading to increased susceptibility to other infections and a reduced ability to fight off diseases. This immune suppression negatively affects reproductive performance by delaying estrus and impairing conception. Implementing strategic deworming programs, improving nutrition, and maintaining clean environments help to prevent helminth infections. By reducing parasitic burdens, dairy farmers can maintain cow health, improve fertility, and achieve long-term sustainability in dairy farming [29].

ENVIRONMENTAL STRESS

Air Pollution Exposure

Air pollution exposure in dairy cows can lead to respiratory distress, reduced immune function, and overall health deterioration, directly affecting reproductive efficiency. Fine particulate matter, gases, and pollutants from industrial or vehicular emissions can exacerbate heat stress and respiratory infections [10]. To mitigate this, providing shelter, improving barn ventilation, and avoiding exposure to polluted areas can help reduce the negative impacts on cow health, improving fertility and supporting sustainable dairy production.

Water Contamination

Contaminated water sources can lead to gastrointestinal infections, reproductive failure, and general health issues in dairy cows. Pollutants, such as heavy metals, bacteria, and chemicals affect cow health and milk production. Ensuring clean water through filtration, regular testing, and proper waste management is essential for maintaining cow health. Clean water also plays a crucial role in reducing stress, supporting fertility, and improving overall sustainability in dairy farming [24].

Soil Mineral Depletion Affecting Feed Quality

Soil mineral depletion negatively impacts the nutritional quality of feed grown on affected soils. The lack of essential minerals, such as calcium, phosphorus, magnesium, and zinc can lead to nutritional imbalances in dairy cows, impairing reproductive health and milk yield. To mitigate this, supplementing feeds with the necessary minerals, using soil amendments, and rotating pastures are important strategies to maintain feed quality and support sustainable dairy farming practices [30].

Excessive Mud Accumulation in Barns

Excessive mud accumulation in barns can lead to hoof infections, lameness, and overall discomfort for dairy cows. This environmental stressor can disrupt cows' ability to move freely, affecting both their health and fertility. Proper barn drainage, regular cleaning, and maintaining dry bedding are key strategies to reduce mud buildup. By providing a clean and comfortable environment, farmers can minimize stress and promote better reproductive performance and overall cow well-being [32].

Poor Ventilation in Housing Systems

Poor ventilation in dairy cow housing systems can lead to high humidity, ammonia buildup, and poor air quality, all of which contribute to respiratory issues, heat stress, and reduced fertility. Ensuring proper airflow through the using of fans, vents, and open barns is essential for cow health [33]. A well-ventilated environment reduces the risk of respiratory infections and stress, enhancing reproductive health and contributing to the long-term sustainability of dairy farming.

Ammonia Buildup from Manure

Ammonia buildup in barns, primarily from manure, can severely impact cow health, leading to respiratory problems and decreased fertility. Ammonia exposure irritates the respiratory system, reduces immune function, and stresses cows, which negatively affects reproductive performance.

Regular cleaning of manure, improved waste management systems, and proper ventilation can reduce ammonia buildup, helping to maintain cow health and reproductive efficiency while supporting sustainable farming practices [34].

Heavy Metal Contamination in Pastures

Heavy metal contamination in pastures from industrial or agricultural runoff can adversely affect cow health, leading to infertility, toxicity, and reduced milk production. Accumulation of metals, such as lead, cadmium, and mercury in the soil can be absorbed by plants and ingested by cows [20]. To mitigate the risk, farmers should regularly monitor pasture soil for heavy metal contamination, rotate grazing areas, and limit exposure to contaminated land. Reducing heavy metal exposure helps preserve cow health, fertility, and sustainable dairy production.

Prolonged Drought Periods

Prolonged drought periods reduce the availability and quality of forage, leading to nutritional deficiencies and water scarcity, both of which hinder reproductive efficiency in dairy cows. Drought conditions can increase stress levels and lower feed intake, causing cows to become undernourished and less fertile. Implementing water conservation practices, providing supplemental feeds, and improving water management can help maintain cow health and reproductive performance during drought conditions, promoting sustainability in dairy farming [35].

Flooding Events

Flooding events can disrupt pastures, contaminate water supplies, and create breeding grounds for pests and diseases. Dairy cows affected by flooding may experience stress, injury, or reduced access to quality feed and clean water, all of which negatively impact reproductive performance. To mitigate flooding impacts, farmers should invest in flood-resistant infrastructure, implement effective water management strategies, and plan for post-flood recovery to ensure that cows remain healthy, fertile, and productive in the aftermath of such events [5].

Soil Erosion Reducing Pasture Productivity

Soil erosion, often caused by heavy rainfall or improper land management, reduces the fertility and productivity of pastures. Eroded soils lose essential nutrients, which leads to poor-quality forage and, consequently, reduced milk production and reproductive efficiency in dairy cows. Preventing soil erosion using cover crops, rotational grazing, and proper land management practices can improve pasture quality, ensuring that dairy cows receive adequate nutrition, supporting their fertility, and promoting sustainable dairy farming [36, 37].

MANAGEMENT-RELATED STRESS

Inadequate Heat Abatement Strategies

Inadequate heat abatement strategies increase the exposure of dairy cows to thermal stress, impacting fertility, milk production, and overall health. Without proper cooling systems like fans, misters, or shade structures, cows suffer from heat stress, leading to hormonal imbalances and decreased reproductive performance [38]. To mitigate this, implementing effective cooling systems, managing barn temperature, and providing adequate water can help reduce heat-related stress and enhance cow fertility, promoting sustainable dairy farming practices.

Poor Housing Design

Poor housing design can create environmental stress by restricting airflow, increasing humidity, and providing inadequate space for cows to move freely. Suboptimal housing reduces comfort, increasing stress levels, and impairs both health and reproductive performance. Proper barn design should prioritize ventilation, space, and cow comfort to reduce stress, enhance cow well-being, and improve reproductive outcomes, contributing to a more sustainable and productive dairy farm [25].

Overcrowding in Dairy Sheds

Overcrowding in dairy sheds leads to stress, reduced mobility, and insufficient resting space, all of which negatively affect cow health and reproduction. Cows kept in overcrowded conditions experience physical discomfort, stress-related illnesses, and diminished fertility. Managing herd size, providing adequate space for each cow, and improving barn layout to ensure comfort are key measures to prevent overcrowding. These practices enhance reproductive performance and promote sustainable dairy farming [39].

Infrequent Reproductive Monitoring

Infrequent reproductive monitoring leads to delayed identification of reproductive issues, reduced fertility rates, and overall lower reproductive success. Regular monitoring of estrus cycles, pregnancy status, and health conditions is essential for timely intervention and effective reproductive management. To improve fertility and reproductive outcomes, implementing consistent reproductive checks, tracking estrus behavior, and using reproductive technologies will ensure that cows are bred at the optimal time, fostering sustainability and efficiency in dairy production [32].

Inefficient Estrus Detection

Inefficient estrus detection delays insemination timing, resulting in reduced conception rates and extended calving intervals. Poor estrus detection, whether through human error or inadequate technology, leads to missed breeding opportunities. By using heat detection aids, improving observation techniques, and training farm personnel, dairy farmers can enhance estrus detection, ensure timely insemination, and improve fertility, contributing to higher productivity and more sustainable dairy farming practices [40].

Delayed Insemination Timing

Delayed insemination timing results in missed opportunities for conception and prolonged calving intervals, leading to reduced reproductive efficiency and overall farm productivity. Accurate and timely insemination is essential for optimizing reproductive performance in dairy cows. Implementing efficient estrus detection and precise timing of artificial insemination (AI) can enhance conception rates, reduce the time between calving events, and increase productivity, supporting more sustainable dairy farming [26].

Poor Artificial Insemination Techniques

Poor artificial insemination (AI) techniques lead to reduced conception rates, contributing to economic losses and extended calving intervals. Incorrect semen handling, improper insemination timing, and lack of expertise can hinder AI success. Training personnel in proper AI techniques, using high-quality semen, and ensuring optimal insemination timing can significantly improve reproductive outcomes, leading to better fertility rates, improved cow health, and more sustainable dairy production practices [38].

High-Stress Handling and Transportation

High-stress handling and transportation negatively impact dairy cows' reproductive performance by increasing cortisol levels, disrupting hormonal balance, and compromising fertility. Stressful events like rough handling, long transport times, and inadequate loading facilities lead to lower conception rates and health issues [25]. Implementing gentle handling techniques, reducing transport times, and using stress-reducing interventions like proper loading facilities and pre-transport acclimatization can minimize stress and improve reproductive health, contributing to the long-term sustainability of dairy farming.

Poor Record-Keeping for Reproductive Performance

Poor record-keeping for reproductive performance results in missed opportunities for timely interventions, inefficient breeding programs, and decreased reproductive success. Accurate and

consistent documentation of estrus cycles, insemination dates, and pregnancy status is essential for identifying trends, monitoring reproductive health, and optimizing breeding strategies. Implementing digital record-keeping systems and ensuring that farm personnel maintain accurate data can improve reproductive management, leading to higher fertility rates, enhanced productivity, and greater sustainability in dairy farming [39].

Lack of Trained Personnel for Reproduction Management

A lack of trained personnel for reproduction management leads to suboptimal breeding decisions, poor estrus detection, and improper handling of reproductive health issues. Ensuring that farm personnel are adequately trained in reproductive management, including estrus detection, AI techniques, and monitoring reproductive health, is crucial for improving fertility rates and productivity [26, 32, 40]. Investing in training programs for staff can enhance the overall reproductive performance of the herd, leading to more sustainable and efficient dairy farming.

GENETIC AND PHYSIOLOGICAL STRESS

Poor Genetic Selection for Heat Tolerance

Poor genetic selection for heat tolerance exacerbates reproductive stress in tropical dairy cows, as they are unable to cope with elevated temperatures. Cows lacking heat tolerance genes are more susceptible to heat stress, leading to reduced fertility and increased embryonic loss. Focusing on selecting for heat-tolerant traits, such as increased sweat gland activity and improved thermoregulatory capacity, can help breed cows that perform better under high-temperature conditions, ensuring sustained reproductive success and productivity in tropical climates [41].

Reduced Fertility in High-Yielding Cows

High-yielding dairy cows are often more susceptible to reproductive issues, as their energy and nutritional demands can outpace their ability to maintain reproductive health. These cows experience metabolic stress, which can impair ovulation, conception, and postpartum recovery. Focusing on balanced genetic selection, proper nutrition, and management practices will help mitigate these effects, ensuring both high yield and reproductive efficiency, promoting sustainable dairy farming [24].

Prolonged Anestrus Postpartum

Prolonged anestrus postpartum, where cows fail to resume normal estrous cycles after calving, can delay conception and increase calving intervals. This condition is often linked to metabolic stress, poor nutrition, or hormonal imbalances. To reduce prolonged anestrus, farmers should implement improved nutritional management, stress reduction strategies, and regular health monitoring, ensuring cows return to optimal reproductive function for a more sustainable dairy operation [42].

Delayed Puberty in Heifers

Delayed puberty in heifers negatively impacts the timing of first calving, extending the productive lifespan of dairy cows and affecting overall herd productivity. Factors, such as inadequate nutrition, hormonal imbalances, and environmental stressors contribute to delayed puberty. Enhancing growth rates through proper feeding, reducing stressors, and genetic selection for earlier maturation can help mitigate delayed puberty and improve reproductive efficiency, promoting sustainable dairy farming practices [43].

Genetic Predisposition to Metabolic Disorders

Genetic predisposition to metabolic disorders, such as ketosis and fatty liver, can negatively affect dairy cows' reproductive performance by disrupting energy metabolism and hormonal balance. These disorders often result in poor fertility, longer calving intervals, and increased culling rates. Genetic selection for better metabolic resilience, along with proper nutrition and management practices, can reduce the risk of metabolic disorders, leading to improved reproductive success and overall farm sustainability [44].

Increased Embryonic Mortality

Increased embryonic mortality, often caused by heat stress, poor nutrition, or infections, reduces fertility and impacts reproductive efficiency. Embryonic losses in early pregnancy can result in significant economic losses due to delayed calving and reduced milk production. Addressing factors, such as heat stress, optimizing nutrition, and ensuring good management practices during early pregnancy can reduce embryonic mortality, improve fertility rates and contributing to more sustainable dairy farming [40].

Shortened Estrous Cycle Duration

A shortened estrous cycle duration can lead to reduced fertility by causing fewer opportunities for successful conception. Shorter cycles are often associated with hormonal imbalances, stress, and poor nutrition. Ensuring that cows receive adequate nutrition, minimize environmental stress, and monitor hormonal health regularly can prevent the occurrence of shortened estrous cycles, enhance reproductive efficiency and contributing to more productive and sustainable dairy farming [36].

Hormonal Imbalances

Hormonal imbalances, particularly those involving progesterone and estrogen, can interfere with estrous cycles, ovulation, and conception rates in dairy cows. These imbalances are often triggered by stress, poor nutrition, or underlying metabolic issues. Effective management strategies, including nutritional optimization, stress reduction, and hormone treatments, when necessary, are crucial for restoring hormonal balance, improving fertility rates, and ensuring reproductive success in dairy herds [42].

Poor Adaptability of Exotic Breeds

Exotic breeds, often introduced for their higher milk yield, may struggle to adapt to the harsh tropical climate. These breeds tend to have poor heat tolerance and are more susceptible to heat stress, leading to reduced fertility and overall reproductive efficiency. Crossbreeding with local heat-tolerant breeds or selecting for traits, such as thermoregulation and heat resilience can improve adaptability, maintaining both high yield and reproductive health in tropical conditions, supporting sustainable dairy farming [45].

Low Heritability of Fertility Traits in Tropical Breeds

The low heritability of fertility traits in tropical breeds presents a challenge in improving reproductive performance through genetic selection [24, 36, 41, 44]. Fertility traits like conception rates, calving intervals, and heat detection are difficult to improve solely through breeding, which can impede progress toward more efficient reproductive systems. Implementing advanced breeding techniques, along with better management practices, can help overcome this challenge, enhancing reproductive performance and sustainability in tropical dairy farming.

METABOLIC DISORDERS

Ketosis

Ketosis occurs when dairy cows mobilize fat reserves to meet energy demands, leading to an accumulation of ketone bodies in the bloodstream. This metabolic disorder is often seen during early lactation and can impair fertility, reduce milk production, and increase susceptibility to infections [18]. Preventing ketosis involves ensuring proper nutritional management, including providing adequate energy during the transition period, and implementing strategies to monitor cow health and metabolic status to maintain reproductive health and overall productivity.

Subclinical Acidosis

Subclinical acidosis, characterized by low rumen pH without overt clinical signs, affects dairy cows' digestive and metabolic health, leading to reduced feed intake, poor digestion, and impaired nutrient absorption. This condition can negatively affect fertility by disrupting rumen fermentation, lowering

blood calcium levels, and reducing cow performance [29]. Implementing proper feeding strategies to maintain rumen health, such as controlling grain intake and providing buffers, can mitigate subclinical acidosis and improve reproductive efficiency.

Hypocalcemia

Hypocalcemia, or low blood calcium levels, is a common metabolic disorder that affects dairy cows, particularly around calving. It impairs smooth muscle function, increasing the risk of retained placenta and delayed uterine involution, both of which disrupt reproductive function. Preventing hypocalcemia involves ensuring adequate calcium intake during the transition period, using oral calcium supplements, and providing balanced nutrition to maintain calcium homeostasis, supporting improved fertility and reproductive success [9].

Retained Placenta

Retained placenta occurs when the placenta does not detach from the uterus after calving, increasing the risk of infections and metabolic imbalances. This condition can significantly delay uterine involution and affect future fertility. Effective management includes ensuring proper nutrition, minimizing stress during parturition, and addressing any metabolic disorders that may predispose cows to retained placenta, thereby improving reproductive outcomes and promoting herd sustainability [19].

Fatty Liver Syndrome

Fatty liver syndrome occurs when excessive fat accumulates in the liver, impairing its function and leading to decreased fertility, poor milk production, and susceptibility to infections. This condition is common in high-yielding dairy cows during the early lactation period. Preventing fatty liver syndrome requires optimizing nutrition, reducing stress, and ensuring proper energy balance during the transition period, which improves metabolic health and reproductive performance, fostering sustainable dairy farming practices [35].

Ruminal Indigestion

Ruminal indigestion, characterized by inefficient fermentation in the rumen, leads to poor nutrient absorption and digestion, which can negatively impact cow health and fertility. Imbalances in diet, like excessive fiber or poor-quality forage, contribute to this condition. Proper management includes providing balanced diets that support rumen health, monitoring feed quality, and minimizing stress factors to improve ruminal function, thereby enhancing reproductive performance and promoting sustainable dairy production [18].

Insulin Resistance Affecting Ovarian Function

Insulin resistance, which reduces the cow's ability to utilize glucose efficiently, can disrupt ovarian function, impair estrous cycles and reducing fertility. This metabolic disorder is often associated with obesity, poor nutrition, and metabolic stress. Managing insulin resistance requires a focus on optimizing energy balance, controlling body condition scores, and providing a balanced diet to support ovarian health, thereby improving fertility and reproductive outcomes in dairy cows [29].

Mineral Toxicity

Mineral toxicity, including excess iron and manganese, can interfere with reproductive health by disrupting hormonal balance and impairing ovarian function. High levels of these minerals can also lead to oxidative stress and decreased immune function. Managing mineral intake and ensuring proper supplementation is crucial to preventing toxicity, supporting healthy reproductive cycles, and maintaining sustainable dairy production, while avoiding negative effects on cow fertility [9].

Oxidative Stress-Induced Fertility Decline

Oxidative stress, caused by an imbalance between free radicals and antioxidants in the body, can damage cells, including those in the reproductive system, leading to reduced fertility. Factors like heat stress, poor nutrition, and metabolic disorders exacerbate oxidative stress. Mitigating oxidative stress

involves providing cows with antioxidants in their diet, optimizing nutritional intake, and minimizing stressors to protect reproductive health and improve fertility, ensuring better reproductive success and farm sustainability [19].

Protein-Energy Malnutrition

Protein-energy malnutrition occurs when dairy cows do not receive adequate protein and energy in their diet, leading to weight loss, metabolic disorders, and impaired reproductive performance. This condition is particularly problematic in high-yielding cows that have increased energy and protein demands. Preventing protein-energy malnutrition requires balanced feeding strategies, including providing high-quality forages, protein supplements, and ensuring cows meet their energy needs, which supports optimal fertility and overall cow health for sustainable dairy farming [35].

BEHAVIORAL AND SOCIAL STRESS

Aggression Due to Hierarchical Dominance

Aggression resulting from hierarchical dominance within dairy herds can lead to social stress, injuries, and reduced overall welfare. Dominant cows often assert control over subordinate cows, limiting their access to food, water, and resting areas [4, 7]. These stressful interactions can also disrupt reproductive cycles, delay estrus, and reduce fertility. Management strategies that reduce aggression, such as providing ample space and careful herd management, can minimize stress and improve reproductive success [46].

Isolation Stress in Confined Housing

Isolation stress occurs when dairy cows are housed separately or removed from familiar social groups, leading to anxiety and reduced welfare. This stress can negatively affect reproduction by causing hormonal imbalances, reduced feed intake, and diminished milk production. Ensuring that cows have opportunities for social interaction, along with providing group housing systems that reflect natural herd dynamics, can mitigate isolation stress and support reproductive health and productivity [22].

Disrupted Circadian Rhythms

Disrupted circadian rhythms, often caused by irregular light exposure or inconsistent feeding schedules, can impair reproductive function in dairy cows [47–49]. Disruptions to the natural light-dark cycle can affect hormone regulation, including melatonin and cortisol levels, which are crucial for maintaining reproductive health. Establishing consistent light-dark cycles and feeding schedules can restore circadian rhythms, promoting better fertility and reproductive efficiency in dairy cows [12].

Noise Pollution Affecting Endocrine Stability

Noise pollution, caused by machinery, traffic, or human activity, can disrupt the endocrine system of dairy cows, leading to stress-induced hormonal imbalances. Chronic exposure to high noise levels can increase cortisol levels, impair immune function, and negatively impact reproductive health. Managing noise levels in housing areas and ensuring a quiet, calm environment can help stabilize endocrine function, reducing stress and supporting reproductive efficiency in dairy cows [46].

Social Instability Due to Herd Changes

Frequent changes in herd composition, such as the introduction of new cows or the removal of others, can lead to social instability, resulting in stress and aggression among cows. Social instability often disrupts feeding patterns, reproductive cycles, and overall herd health [47–49]. To reduce social stress, it is essential to limit sudden changes in herd composition, gradually introduce new cows, and provide adequate space to maintain social harmony, enhancing reproductive performance [46].

Long-Distance Transportation Stress

Long-distance transportation of dairy cows can cause significant physical and psychological stress, negatively impacting fertility, immune function, and milk production. Prolonged transportation exposes cows to cramped conditions, heat stress, and limited access to food and water, which disrupts their

reproductive cycles. Proper transportation management, including frequent rest stops, access to water, and climate control, can reduce the negative impact of transportation on reproductive health and support sustainable dairy farming [46].

Inadequate Access to Shaded Resting Areas

Lack of access to shaded resting areas, particularly in hot climates, can cause heat stress, leading to reduced feed intake, higher body temperatures, and impaired reproductive function. Insufficient shade exacerbates thermal stress, causing cows to spend less time resting and more time in stressful, high-temperature conditions. Providing ample shaded areas and adequate shelter in housing systems is essential for maintaining comfort, reducing heat stress, and supporting reproductive health [46].

Lack of Enrichment Leading to Boredom

Lack of environmental enrichment in dairy cows' living spaces can lead to boredom, which can result in behavioral issues like increased aggression, repetitive behaviors, and reduced welfare. Boredom-induced stress can also affect reproductive cycles by disrupting hormonal balances [13, 14, 29]. Providing enrichment through feeding routines, objects for interaction, and opportunities for movement can improve cow welfare, reduce stress, and contribute to improved reproductive outcomes by enhancing overall health and reducing behavioral stress.

Nighttime Light Pollution Affecting Melatonin Levels

Nighttime light pollution, which alters the natural dark period of cows' circadian rhythms, can disrupt melatonin production. Melatonin is crucial for regulating reproductive hormones and maintaining a regular estrous cycle. Exposure to artificial light at night can interfere with hormonal cycles, leading to delayed estrus and reduced fertility. Ensuring minimal artificial lighting during nighttime and promoting natural light exposure can support the regulation of melatonin levels, thereby improving reproductive performance in dairy cows [6, 17, 33, 50].

Poor Maternal Bonding in Heifers

Poor maternal bonding in heifers, often due to early weaning or inadequate maternal care, can lead to stress, behavioral issues, and delayed puberty. This lack of bonding affects the heifer's emotional stability, which in turn can disrupt reproductive cycles and reduce fertility. Providing proper maternal care, including natural weaning practices and adequate socialization, can improve maternal bonding, support early reproductive development and enhancing fertility in heifers [46].

CLIMATE CHANGE-ASSOCIATED STRESS

Erratic Rainfall Patterns

Erratic rainfall patterns due to climate change can lead to unpredictable water availability and negatively affect pasture growth, reducing feed availability for dairy cows [47–49]. Inconsistent rainfall can also result in poor water quality, which further exacerbates dehydration and nutritional stress. To mitigate these effects, implementing water conservation techniques and optimizing feed management practices are essential for maintaining cow health, reproductive function, and farm sustainability [51].

Increased Frequency of Heatwaves

Increased frequency of heatwaves as a result of climate change heightens thermal stress on dairy cows, leading to reduced fertility, increased susceptibility to diseases, and lower milk production. Prolonged exposure to extreme heat impacts cows' ability to regulate body temperature and can cause severe dehydration. Implementing cooling systems, providing adequate shade, and adjusting feeding schedules during peak heat periods can alleviate heat stress and protect reproductive health [16].

Rising Nighttime Temperatures

Rising nighttime temperatures disrupt the natural cooling process for dairy cows, which usually occurs during the night. This sustained warmth prevents cows from recovering from daytime heat stress, leading to a continuous strain on their thermoregulatory systems. Ensuring proper ventilation and

nighttime cooling systems in barns, along with managing herd behavior, can mitigate the negative impact of rising nighttime temperatures on reproductive health and overall cow productivity [2].

Reduced Pasture Productivity

Desertification caused by climate change reduces the availability of productive pastures, limiting forage options for dairy cows. Lower pasture quality leads to nutritional deficiencies, affecting fertility and cow health. Sustainable land management practices, like reforestation, soil conservation, and implementing drought-resistant forage crops, can help maintain pasture productivity, ensuring a stable food supply and supporting reproductive health in dairy cows [52].

Higher Carbon Dioxide

Rising carbon dioxide levels influence plant growth and nutrient composition, potentially reducing the nutritional quality of forage. This decrease in forage quality can result in protein and mineral deficiencies, affecting the reproductive health of dairy cows. Farmers can mitigate this stress by diversifying feed sources, supplementing cows' diets with high-quality feed, and optimizing feeding strategies to ensure cows receive the necessary nutrients to support reproductive function [53].

Expansion of Disease Vectors

Warming temperatures associated with climate change increase the geographic range of disease vectors, like mosquitoes, ticks, and flies, which can transmit harmful pathogens. The spread of vector-borne diseases like mastitis, trypanosomiasis, and tick-borne diseases can compromise cow health and fertility. Effective vector control strategies, including using insecticides, proper pasture management, and the development of disease-resistant breeds, can reduce the impact of these emerging health threats [26].

Extreme Weather Events

Extreme weather events like cyclones and hurricanes are becoming more frequent and intense due to climate change [7, 31, 54]. These events can cause direct physical harm to dairy cows, destroy infrastructure, disrupt feed and water supplies, and lead to severe economic losses. Implementing disaster preparedness plans, including strengthening barn structures, securing feed storage, and establishing emergency response protocols, can help mitigate the damage caused by extreme weather events and ensure the continuation of dairy production.

Changes in Monsoon Patterns

Shifts in monsoon patterns affect the timing and intensity of rainfall, which in turn impacts the growth and availability of seasonal feed crops. These changes lead to irregular feed cycles, causing nutritional stress and reduced fertility in dairy cows. Adapting farming practices to new climatic conditions by utilizing drought-resistant crops, improving feed storage, and adjusting feeding schedules will help mitigate the negative effects of changing monsoon patterns on reproductive health [47, 55–57].

Salinity Intrusion Affecting Water and Feed Resources

Salinity intrusion caused by rising sea levels and extreme weather events impacts water quality and the availability of fresh water for dairy cows. Additionally, it can affect the nutritional quality of feed crops grown near coastal areas. Implementing freshwater management strategies, including rainwater harvesting, desalination, and selecting salt-tolerant forage species, can help safeguard water and feed resources, ensuring cows remain hydrated and well-nourished for optimal reproductive health [58, 59].

Increased Atmospheric Ozone Levels

Increased atmospheric ozone levels, a consequence of climate change, can have harmful effects on dairy cows' respiratory health. Exposure to high ozone concentrations can cause lung damage, stress, and reduced feed intake, which in turn can lead to reproductive challenges. Enhancing ventilation in barns, avoiding peak ozone hours for outdoor grazing, and managing air quality can reduce respiratory stress, maintain cow health and support reproductive efficiency [60, 61].

CONCLUSION

Reproductive efficiency in tropical dairy cows is significantly impacted by a variety of interconnected stressors, including heat, nutritional imbalances, and diseases. Addressing these challenges requires a multifaceted approach that combines heat stress mitigation, optimal nutrition, and effective disease management strategies. The integration of these factors, along with genetic selection for heat tolerance, offers promising solutions to enhance fertility and overall reproductive performance. Moreover, the study highlights the need for sustainable farming practices that consider the effects of climate change and its potential to exacerbate existing challenges. By adopting these integrated strategies, tropical dairy farming can improve reproductive outcomes, ensuring both animal welfare and the long-term sustainability of dairy production in these regions.

Future Directions

Future research should focus on exploring advanced breeding techniques, including genomic selection, to enhance heat tolerance and reproductive traits in tropical dairy cows. Understanding the genetic basis of fertility under stressful environmental conditions will allow for the development of more resilient livestock. Additionally, studies on the long-term impacts of climate change on reproductive performance are essential to predict and mitigate future challenges. The role of alternative feeds, such as agro-industrial by-products and forages rich in antioxidants, should be investigated further to improve nutritional strategies for sustaining fertility in tropical climates. Moreover, precision livestock farming technologies that monitor and manage environmental conditions, animal health, and reproductive cycles in real-time hold great potential for improving reproductive efficiency. Lastly, investigating the interactions between microbial health, nutrition, and fertility in tropical dairy systems could provide new insights into optimizing reproductive outcomes through gut health management.

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