STM JOURNALS

Research & Reviews: A Journal of
Crop Science and Technology

ISSN: 2319-3395
Volume 14, Issue 3, 2025
September–December
DOI (Journal): 10.37591/RRJoCST

https://journals.stmjournals.com/rrjocst

Review RRJoCST

Optimizing Green Fodder Availability: Strategic Roadmaps for Sustainable Dairy Development in the Tropics

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Abstract

The growing demand for dairy products in tropical regions underscores the urgent need to optimize green fodder availability for sustainable dairy farming. Green fodder serves as a vital source of nutrition for dairy cows, directly influencing milk yield, animal health, and overall farm profitability. However, challenges such as limited land availability, erratic weather patterns, and competition for resources hinder consistent fodder production. The present review highlighted innovative strategies to enhance green fodder availability, including the adoption of high-yielding fodder species, integration of agroforestry systems, utilization of hydroponic and vertical farming techniques, and efficient crop rotation practices. Special emphasis was placed on the role of climate-resilient fodder varieties and precision agriculture technologies to mitigate environmental constraints. The importance of community-based initiatives, such as fodder banks and cooperative farming models, was also discussed as a means to ensure year-round fodder supply. By synthesizing recent advances and practical approaches, the present study provided a comprehensive roadmap for improving green fodder accessibility in the tropics. These strategies aim to foster sustainable dairy development while addressing nutritional security, environmental conservation, and economic viability. Optimizing green fodder resources can revolutionize dairy farming in the tropics, promoting resilience and sustainability in an era of growing agricultural challenges.

Keywords: Climate-resilient fodder, fodder banks, fodder cultivation, green fodder availability, high-yielding fodder species, precision agriculture

INTRODUCTION

Rapid expansion of dairy farming in the tropics has intensified the demand for quality green fodder—a critical component of dairy cow nutrition [1]. Green fodder not only enhances milk yield and quality but also supports overall animal health and reproductive performance [2, 3]. However, the availability of green fodder in tropical regions remains inconsistent due to challenges such as land scarcity, water shortages, seasonal variations, and the rising competition for arable land to grow food crops [4, 5]. Addressing these challenges is essential to ensure the sustainability of dairy farming systems while minimizing production costs and maximizing profitability for farmers [6, 7].

Numerous approaches have been explored to improve green fodder production in the tropics, including the introduction of high-yielding and drought-resistant fodder varieties, the adoption of integrated crop-livestock systems, and the use of innovative practices such as hydroponic fodder cultivation and agroforestry [8–11]. Additionally, advancements in precision agriculture and irrigation

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Received Date: July 04, 2025
Accepted Date: July 07, 2025
Published Date: July 21, 2025

Citation: Md. Emran Hossain. Optimizing Green Fodder Availability: Strategic Roadmaps for Sustainable Dairy Development in the Tropics. Research & Reviews: Journal of Crop Science and Technology. 2025; 14(3): 11–30p.

technologies have shown promise in optimizing resource use and enhancing fodder yield [6, 12, 13]. Despite these efforts, widespread adoption of such practices has been limited due to socio-economic barriers, lack of awareness, and insufficient access to resources, leaving a significant gap in sustainable fodder availability for dairy systems [11, 14–19].

The present study provided a comprehensive roadmap to address these challenges by integrating advanced scientific insights with practical, region-specific solutions for the tropics. The novelty of this work lies in its multidisciplinary approach, combining traditional and innovative techniques to improve green fodder availability while addressing socio-economic and environmental constraints. By emphasizing climate-resilient strategies, community-based interventions, and the application of cutting-edge technologies, the present study proposed scalable and cost-effective solutions for sustainable dairy farming. The findings aim to contribute significantly to the existing knowledge, providing a blueprint for improving dairy productivity and sustainability in tropical regions.

IMPROVED CULTIVATION PRACTICES

Use of High-Yielding Fodder Varieties

Introducing high-yielding and climate-resilient fodder varieties can enhance productivity under tropical conditions [10, 20, 21]. These varieties are designed to withstand abiotic stresses such as drought, heat, and low soil fertility, ensuring consistent fodder supply. Promoting the adoption of such varieties through farmer education, government subsidies, and seed availability can revolutionize fodder production, addressing both nutritional and economic challenges in dairy farming.

Proper Crop Rotation Systems

Implementing crop rotation systems prevents soil degradation, enhances fertility, and supports sustainable fodder production [4, 12, 22]. Alternating fodder crops with cereals, pulses, or oilseeds improves nutrient cycling and reduces pest infestations. Strategically planned rotations ensure a balanced ecosystem, leading to higher yields and reduced input costs, while providing an environmentally sound solution to improve green fodder availability in tropical dairy farming systems.

Adoption of Mixed Cropping Techniques

Mixed cropping involves cultivating two or more crops simultaneously on the same field, maximizing land use efficiency and improving fodder availability. Combining fodder grasses with legumes or cereals enhances biomass yield and soil fertility [10, 20, 21]. This practice not only diversifies income sources for farmers but also provides a balanced feed resource for dairy cattle, ensuring sustainable productivity.

Integration of Legumes in Cropping Systems

Incorporating legumes into fodder cropping systems offers multiple benefits, including enhanced soil nitrogen fixation, improved fodder quality, and reduced dependency on chemical fertilizers [14, 19, 23]. Legumes such as cowpea, lucerne, or clover can be intercropped or rotated with grasses to boost yield and nutritional value. This sustainable practice contributes significantly to addressing the feed deficit in tropical dairy farming.

Timely Sowing and Harvesting Practices

Timely sowing and harvesting are critical for maximizing fodder yield and nutritional value. Early sowing ensures crops utilize optimal growing conditions, while timely harvesting prevents nutrient losses [24, 25]. Proper scheduling based on crop growth stages, climatic conditions, and seasonal variations reduces wastage and enhances fodder quality, ensuring a consistent and sustainable feed supply for dairy cattle.

FERTILIZER AND SOIL MANAGEMENT

Organic Manure Application

Applying organic manure improves soil structure, enhances nutrient availability, and promotes healthy fodder growth [7, 26, 27]. Organic manures such as compost, farmyard manure, and poultry litter enrich the soil with essential macro- and micronutrients, improve water retention, and enhance microbial activity. This sustainable practice reduces the dependency on chemical fertilizers and boosts the overall health and productivity of fodder crops in dairy systems.

Biofertilizer Utilization

Biofertilizers, such as nitrogen-fixing bacteria and mycorrhizal fungi, help improve soil fertility and increase fodder crop yields [28–30]. These microbial inoculants enhance nutrient uptake, particularly nitrogen, phosphorus, and other trace elements, reducing the need for chemical fertilizers. By promoting soil health and increasing fodder productivity, biofertilizers contribute to sustainable farming practices, reducing environmental impact and improving cost-effectiveness in dairy systems.

Soil Testing for Optimal Nutrient Application

Soil testing is essential for determining nutrient deficiencies and ensuring that the right fertilizers are applied in the correct amounts [7, 26, 27]. Regular soil testing helps farmers optimize nutrient management, preventing over-fertilization and reducing environmental pollution. By tailoring nutrient application to the specific needs of fodder crops, soil testing ensures improved yield, better feed quality, and more efficient use of resources in dairy farming systems.

Proper Weed Management

Effective weed management is crucial for maximizing fodder crop yield and maintaining soil health. Weeds compete with fodder crops for water, nutrients, and sunlight, reducing overall productivity [7, 26, 27]. Integrated weed management practices, such as mulching, crop rotation, and the use of selective herbicides, can minimize weed growth while promoting healthy, vigorous fodder crops. Proper weed control leads to better fodder availability for dairy cattle.

Balanced Fertilization Practices

Balanced fertilization practices ensure that fodder crops receive the optimal nutrients they need for growth, minimizing nutrient imbalances in the soil [28–30]. Using a combination of organic and inorganic fertilizers tailored to soil needs improves fodder crop health and quality. This practice enhances soil fertility, prevents overuse of specific nutrients, and supports sustainable dairy farming by increasing fodder production and reducing input costs.

IRRIGATION MANAGEMENT

Drip irrigation Systems

Drip irrigation systems deliver water directly to the root zone of crops, minimizing water wastage and ensuring uniform moisture distribution [31–33]. This technique is particularly beneficial for fodder crops in water-scarce areas, as it reduces evaporation losses and ensures efficient water use. Drip systems improve fodder quality and yield by providing consistent, targeted irrigation, enhancing the sustainability of dairy farming operations.

Sprinkler Irrigation Methods

Sprinkler irrigation systems distribute water evenly over fodder crops, simulating natural rainfall. This method is especially effective for large-scale fodder cultivation, as it covers extensive areas efficiently [34–37]. Sprinklers help maintain uniform moisture levels, promoting healthy crop growth and preventing water stress. By enhancing water distribution and reducing water wastage, sprinklers contribute to more sustainable and productive fodder farming practices.

Rainwater Harvesting for Fodder Fields

Rainwater harvesting involves capturing and storing rainwater for later use in fodder irrigation. This practice reduces dependency on external water sources, lowers irrigation costs, and ensures a reliable water supply during dry periods [31–33]. Implementing rainwater harvesting systems, such as ponds, tanks, and catchment areas, can improve fodder production efficiency, especially in regions with seasonal rainfall variability, promoting water sustainability in dairy farming.

Timely Irrigation Scheduling

Timely irrigation scheduling is essential for optimizing water use and enhancing fodder production [34–37]. By aligning irrigation practices with crop growth stages and local climate patterns, farmers can maximize water efficiency, reduce wastage, and improve crop yield. Proper scheduling prevents water stress, ensuring healthy fodder crops for dairy cattle. It also helps conserve water resources, contributing to sustainable farming practices in water-scarce regions.

Use of Drought-Resistant Fodder Varieties

Drought-resistant fodder varieties are specially developed to thrive in areas with limited water availability. These varieties are genetically adapted to withstand long dry spells, maintaining consistent growth and yield during drought conditions [31–33].

Using drought-resistant fodder varieties helps ensure year-round fodder supply, reduces water dependence, and provides a sustainable solution for maintaining dairy cattle nutrition, even in regions with unpredictable rainfall.

EFFICIENT LAND UTILIZATION

Promotion of Fodder Banks

Fodder banks are community-based or farm-level storage systems designed to stockpile surplus fodder for lean seasons [8, 10, 38, 39]. By collecting and storing green fodder during periods of abundance, farmers can ensure a consistent supply of nutritious feed year-round. Promoting fodder banks through local cooperatives and farmer networks can help stabilize feed availability, reduce dependency on external feed sources, and enhance livestock productivity.

Cultivation on Degraded Lands

Rehabilitating degraded lands for fodder production is a sustainable way to increase green fodder availability [1, 40–42]. By using soil conservation techniques such as agroforestry, contour farming, and organic fertilization, these lands can be restored to productivity. Cultivating drought-tolerant, low-maintenance fodder species on such lands not only improves land health but also increases fodder supply for dairy farming systems.

Vertical Farming Practices for Fodder

Vertical farming offers a modern solution to increase fodder production in limited spaces. This practice involves growing fodder crops in stacked layers using controlled environments. Vertical farming techniques such as hydroponics and aeroponics can significantly increase yield per square meter, making it ideal for urban and peri-urban dairy systems. It ensures a continuous and space-efficient supply of fresh green fodder [8, 10, 38, 39].

Intercropping with Food Crops

Intercropping fodder species with food crops optimizes land use and improves biodiversity. This practice reduces competition for resources, enhances soil fertility through nitrogen fixation, and diversifies farm income [1, 40–42]. Combining crops such as maize or rice with leguminous fodder species ensures efficient land use. It provides a reliable source of nutrition for dairy cattle while contributing to overall farm sustainability.

Use of Field Borders for Fodder Species

Utilizing field borders for growing fodder species is an efficient use of otherwise underutilized land. Growing legumes or grasses along the edges of fields or roadsides helps conserve soil, reduce erosion, and enhance biodiversity [14, 19, 25, 43]. These border areas can provide a supplementary feed source for dairy cattle while simultaneously improving farm aesthetics and environmental health through natural habitat preservation.

INTEGRATED LIVESTOCK-FODDER SYSTEMS

Agri-Silviculture Practices

Agri-silviculture practices integrate trees with agricultural crops, creating a productive ecosystem that supports both fodder production and soil health [7, 19, 26, 44, 45]. By incorporating tree species alongside fodder crops, this system enhances biodiversity, improves water retention, and prevents soil erosion. The trees provide additional feed for livestock while fostering a resilient and sustainable farming environment, contributing to long-term fodder availability for dairy systems.

Silvopastoral Systems

Silvopastoral systems combine livestock grazing with tree-based agriculture, optimizing land use while enhancing fodder production [7, 19, 26, 44, 45]. Trees in these systems provide shade, improve soil fertility, and offer additional fodder resources such as leaves and pods. This integrated approach improves animal welfare, increases fodder yield, and promotes environmental sustainability, making it an effective strategy for improving green fodder availability in dairy farming systems.

Use of tree fodder species like Leucaena

Tree fodder species such as Leucaena are highly nutritious and drought-resistant, making them ideal for tropical dairy systems [7, 19, 26, 44, 45]. Leucaena trees provide high-protein forage for dairy cattle, especially during dry seasons when grass availability is limited. Incorporating such tree species into fodder systems enhances feed quality, reduces dependency on external feed sources, and supports sustainable livestock production in resource-limited environments.

Incorporation of Fodder Shrubs

Fodder shrubs, such as Morus and Gliricidia, provide a valuable supplement to traditional green fodder crops. These shrubs are highly nutritious, resilient, and adaptable to diverse climatic conditions [7, 19, 26, 44, 45]. By incorporating fodder shrubs into farming systems, farmers can ensure a reliable source of feed throughout the year, especially during lean periods. This practice enhances feed security and contributes to sustainable dairy farming practices.

Use of Alley Cropping Systems

Alley cropping systems involve planting rows of trees or shrubs between crop fields—creating alleyways for fodder cultivation. This practice helps optimize land use by diversifying farm income and providing additional fodder resources [7, 19, 26, 44, 45]. Alley cropping enhances soil fertility, conserves water, and reduces wind erosion. The integration of fodder crops in these systems ensures a consistent supply of green feed for dairy cows while improving farm sustainability.

CROP-SPECIFIC INNOVATIONS

Development of Dual-Purpose Crops

Development of dual-purpose crops focuses on breeding varieties that can serve both as human food and livestock fodder [7, 26, 44, 45]. These crops provide a versatile solution for farmers, offering both nutritional benefits for livestock and marketable products for human consumption. Dual-purpose crops maximize land use efficiency, enhance farm profitability, and contribute to food and feed security, making them a sustainable option in diverse agricultural systems.

Intensification of Napier Grass Cultivation

Intensification of Napier grass cultivation involves increasing the productivity of this high-yielding fodder crop through improved management practices. Techniques such as optimized fertilization, irrigation, and pest control are used to boost yield [7, 26, 44, 45]. Napier grass is highly nutritious and suitable for both grazing and silage production, making it an essential crop for sustainable dairy farming, especially in tropical regions with limited fodder resources.

Propagation of Sorghum as a Fodder Crop

Propagation of sorghum as a fodder crop focuses on expanding its use as a drought-resistant and high-yielding feed resource. Sorghum is well-suited to arid and semi-arid regions, where water availability is limited [7, 26, 44, 45]. Its cultivation provides a reliable and nutritious fodder source for livestock. Research into improved varieties and cultivation techniques enhances sorghum's role in sustainable livestock systems, contributing to feed security in challenging climates.

Promotion of Maize for Silage

Promotion of maize for silage involves encouraging its use as a high-energy feed for livestock, particularly in the form of well-fermented silage [7, 26, 44, 45]. Maize is an important silage crop due to its high yield and digestibility, making it a key component of balanced rations for dairy cattle. Expanding maize cultivation for silage helps improve fodder availability, reduce feed costs, and enhance productivity in dairy farming systems.

Use of Bajra for Arid Regions

The use of *Bajra* (pearl millet) as a fodder crop in arid regions focuses on utilizing its drought tolerance and high nutritional value for livestock feed. *Bajra* thrives in low-rainfall areas, making it an ideal choice for regions facing water scarcity [7, 26, 44, 45]. As a resilient fodder source, *Bajra* helps improve feed availability, enhance animal productivity, and support sustainable dairy farming practices in challenging environmental conditions.

ALTERNATIVE FEED RESOURCES

Hydroponic Fodder Cultivation

Hydroponic fodder cultivation involves growing fodder crops in a controlled, soil-free environment using nutrient-rich water [23, 33, 46–48]. This method significantly increases fodder yield in limited spaces and reduces water and land usage. Hydroponic systems provide a nutritious and fast-growing feed source for dairy cattle, particularly in areas with land constraints or water scarcity, offering a sustainable alternative for feed production.

Cultivation of Azolla as Green Feed

Azolla—a fast-growing aquatic fern—is an excellent green feed for livestock, rich in proteins, vitamins, and minerals. It thrives in waterlogged conditions, making it ideal for low-lying or flooded areas [23, 33, 46–48]. The cultivation of azolla provides a highly nutritious and sustainable fodder option, reducing reliance on traditional feed crops while improving feed efficiency in dairy farming systems.

Use of Water Hyacinth in Fodder Formulations

Water hyacinth—an aquatic plant—can be used as a valuable fodder resource for dairy cattle. It is rich in fiber and protein and can be utilized as a supplementary feed, especially in areas with abundant water sources. By incorporating water hyacinth into fodder formulations, farmers can reduce the cost of feed, enhance nutrient intake for livestock, and manage invasive species sustainably [23, 33, 46–48].

Growing Fodder Using Saline Water

Growing fodder using saline water is a viable solution for areas with limited fresh water resources [23, 33, 46–48]. Certain salt-tolerant fodder species, such as halophytes, can thrive in saline environments, providing a sustainable feed source for dairy cattle. This practice reduces pressure on freshwater resources, supports sustainable fodder production, and ensures feed availability in drought-prone or water-scarce regions.

Incorporation of Food Industry Byproducts

Incorporating food industry byproducts, such as wheat bran, brewery waste, or fruit pulp, into fodder formulations offers a sustainable way to utilize waste while reducing feed costs. These byproducts are rich in nutrients and can be supplemented to dairy cattle diets to improve feed efficiency [23, 33, 46–48]. This practice supports circular agriculture by recycling waste and ensuring a more sustainable and cost-effective feed supply for dairy systems.

NATURAL RESOURCE MANAGEMENT

Conservation of Fodder Germplasm

Conservation of fodder germplasm involves preserving and maintaining the genetic diversity of fodder species to ensure a sustainable supply of nutritious feed [19, 49–52]. This includes safeguarding native varieties, wild relatives, and improved cultivars that may be at risk of extinction. By conserving fodder germplasm, farmers can access a broad genetic pool for future breeding programmes, ensuring resilience to pests, diseases, and changing climatic conditions.

Sustainable Grazing Practices

Sustainable grazing practices focus on managing pasturelands in a way that preserves soil health, prevents overgrazing, and supports long-term fodder production. Key practices include rotational grazing, maintaining optimal stocking densities, and ensuring adequate rest periods for pastures [19, 49–52]. These practices improve pasture productivity, prevent land degradation, and provide a sustainable feed source for dairy cattle, supporting eco-friendly livestock systems.

Rejuvenation of Natural Grasslands

Rejuvenation of natural grasslands involves restoring degraded grasslands through controlled grazing, reseeding, and improved management practices [19, 49–52]. This process enhances soil fertility, increases plant diversity, and boosts fodder availability for livestock. By rejuvenating grasslands, farmers can secure a sustainable and cost-effective feed supply while contributing to biodiversity conservation and improving the overall health of the ecosystem.

Protection of Common Property Resources

Protection of common property resources (CPRs), such as communal pastures, water bodies, and forests, ensures that these shared resources are used sustainably. Management strategies include setting grazing limits, ensuring equitable resource distribution, and preventing overexploitation [19, 49–52]. Protecting CPRs support fodder availability, promote community resilience, and help maintain the ecological balance, ensuring long-term sustainability of livestock farming in communal areas.

Riverbank Fodder Cultivation

Riverbank fodder cultivation involves growing fodder species along riverbanks, utilizing the fertile soil and water available in these areas. This method enhances fodder availability without competing with prime agricultural land. Riverbanks also act as buffer zones, reducing soil erosion and improving water quality [19, 49–52]. By cultivating fodder along rivers, farmers can access a reliable and sustainable feed source while contributing to environmental conservation.

POST-HARVEST MANAGEMENT

Silage Preparation Techniques

Silage preparation involves fermenting green fodder in anaerobic conditions to preserve its nutritional value for later use [21, 27, 52–54]. Proper chopping, packing, and sealing of the fodder in airtight containers, such as silos or trenches, are essential for effective fermentation. Silage helps provide high-quality feed during the off-season, ensuring a steady supply of nutritious fodder for dairy cattle, even when fresh pasture is unavailable.

Hay-Making for off-Season use

Hay-making involves drying freshly cut fodder to reduce moisture content, preserving it for future use [21, 27, 52–54]. The process includes cutting, drying, and storing fodder in a well-ventilated area. Properly dried hay retains its nutritional value and serves as an essential feed resource during periods of fodder scarcity. This method ensures consistent feed availability for dairy cows, especially during the dry or off-season months.

Proper Storage Facilities

Proper storage facilities are critical for preserving the quality of harvested fodder. Constructing well-ventilated, dry, and rodent-proof storage sheds protects hay, silage, and other fodder types from spoilage, moisture loss, and contamination [21, 27, 52–54]. Ensuring proper storage conditions helps maintain fodder quality, reducing waste and improving the efficiency of fodder use throughout the year, ultimately supporting sustainable dairy farming practices.

Fodder Drying Techniques

Fodder drying techniques, such as sun-drying, shade-drying, or mechanical drying, reduce moisture content and prevent spoilage [21, 27, 52–54]. Proper drying is essential for preserving the nutritional content of fodder, especially when harvesting large amounts during peak production periods. These techniques ensure that fodder can be stored for extended periods and used during lean months, ensuring consistent feed availability for dairy cattle in all seasons.

Use of Baling Methods

Baling is a method of compacting dried fodder into manageable, uniform-sized bundles for easy handling and storage. Using baling machines to compress hay, straw, or silage helps reduce storage space and preserves the quality of the fodder [21, 27, 52–54]. Properly baled fodder is less prone to spoilage, more efficient for transportation, and ensures a reliable supply of feed for dairy cattle, especially during the off-season.

POLICY AND AWARENESS INITIATIVES

Government Incentives for Fodder Cultivation

Government incentives for fodder cultivation can significantly enhance fodder production by providing financial support, subsidies, and tax exemptions to farmers [11, 55–57]. These initiatives help reduce the cost burden on farmers and encourage them to invest in high-quality fodder crops, improving feed availability for dairy farming. Incentives such as grants, low-interest loans, and tax relief contribute to sustainable dairy development by enhancing fodder supply.

Awareness Campaigns for Farmers

Awareness campaigns play a vital role in educating farmers about the importance of sustainable fodder production [11, 55–57]. These campaigns disseminate knowledge on modern fodder cultivation techniques, proper irrigation practices, and the benefits of integrating livestock-fodder systems. By raising awareness, farmers can adopt best practices that optimize fodder yield, improve dairy productivity, and contribute to long-term sustainability in farming systems.

Training Programmes on Fodder Management

Training programmes on fodder management equip farmers with the necessary skills and knowledge to optimize fodder production. These programmes cover topics such as efficient irrigation, crop rotation, pest management, and post-harvest practices [11, 55–57]. By enhancing farmers' capacity to manage fodder crops effectively, training programs ensure improved feed availability, leading to better livestock health, increased productivity, and sustainable dairy farming systems.

Encouraging Community Fodder Plots

Community fodder plots encourage collective action by groups of farmers to grow fodder on shared land [11, 55–57]. This initiative improves resource utilization, reduces individual costs, and enhances fodder supply, particularly in regions with limited land availability. By pooling resources, farmers can access larger areas for fodder cultivation, leading to better yields and ensuring consistent feed availability for dairy cattle across the community.

Subsidized Fodder Seeds

Subsidized fodder seeds make high-quality, high-yielding fodder varieties more accessible to farmers, particularly smallholders [11, 55–57]. By reducing the cost of purchasing seeds, these subsidies encourage farmers to adopt improved fodder varieties that boost productivity and provide better nutritional value for livestock. Subsidized seeds contribute to enhanced feed security, improving the overall sustainability and profitability of dairy farming in long term.

TECHNOLOGY INTERVENTIONS

Use of Mechanized Fodder Harvesters

Mechanized fodder harvesters streamline the process of cutting, chopping, and collecting fodder, reducing labor costs and increasing efficiency [23, 58–61]. These machines ensure uniform harvesting, improve fodder quality by minimizing physical damage, and increase overall productivity. The use of mechanized harvesters helps meet the growing demand for fodder, ensuring a continuous supply of nutritious feed for dairy cattle while saving time and resources.

Application of GIS for Fodder Planning

Geographic Information System (GIS) technology can optimize fodder planning by mapping land suitability, crop growth patterns, and resource availability. By analyzing spatial data, farmers can identify the best locations for fodder cultivation, monitor growth conditions, and forecast potential yield. GIS-driven decision-making enables more precise resource allocation, improving fodder production efficiency and ensuring sustainable feed availability for dairy farming systems [23, 58–61].

Smart Farming Techniques for Fodder Cultivation

Smart farming techniques, such as precision agriculture, integrate technology with traditional farming practices to optimize fodder cultivation. By using sensors, automated irrigation, and data analytics, farmers can monitor soil conditions, weather patterns, and crop health in real time. These techniques help enhance resource use efficiency, reduce waste, and improve the overall yield and quality of fodder crops, ensuring sustainable feed production for dairy systems [23, 58–61].

Mobile Applications for Fodder Advisory Services

Mobile applications for fodder advisory services provide farmers with real-time information on best practices for fodder cultivation, pest management, irrigation schedules, and market trends. These applications can deliver personalized guidance based on location-specific conditions, helping farmers optimize fodder production [23, 58–61]. By promoting knowledge dissemination and facilitating decision-making, mobile applications contribute to more efficient and sustainable fodder management, benefiting dairy farmers and improving feed availability.

Drone Technology for Monitoring Fodder Fields

Drone technology offers an innovative solution for monitoring fodder fields, providing high-resolution aerial imagery and data on crop health, growth stages, and irrigation needs. Drones enable farmers to quickly assess large areas, detect potential issues, and make informed decisions about pest control or nutrient application. This technology improves the precision and efficiency of fodder management, helping farmers increase productivity while minimizing environmental impact [23, 58–61].

CLIMATE-SMART PRACTICES

Cultivation of Climate-Resilient Species

Cultivating climate-resilient fodder species ensures a stable feed supply even under changing environmental conditions [3, 23, 24, 31]. These species are tolerant to drought, heat, and pests, making them ideal for areas prone to climate variability. By selecting robust varieties, farmers can safeguard fodder production, maintain dairy cow health, and enhance overall productivity, ensuring long-term sustainability in dairy systems under climate stress.

Carbon Sequestration through Fodder Trees

Fodder trees, such as Leucaena and Gliricidia, contribute to carbon sequestration by absorbing CO_2 from the atmosphere and storing it in biomass and soil [3, 23, 24, 31]. This process not only reduces greenhouse gases but also improves soil fertility and enhances fodder quality. Incorporating fodder trees into farming systems helps mitigate climate change, while simultaneously improving feed availability and supporting sustainable dairy production practices.

Adoption of No-Till Farming Practices

No-till farming practices reduce soil erosion, enhance water retention, and improve soil structure, contributing to higher fodder yields [3, 23, 24, 31]. By minimizing soil disturbance, no-till farming preserves soil moisture and microbial activity, which is vital for maintaining productive fodder fields, particularly in regions with erratic rainfall. This practice supports sustainable and climate-resilient fodder production, ensuring consistent feed availability for dairy cattle.

Mulching to Conserve Soil Moisture

Mulching involves covering the soil surface with organic materials such as crop residues or straw to retain moisture, regulate temperature, and suppress weed growth [3, 23, 24, 31]. This climate-smart practice improves soil fertility and protects fodder crops from drought stress, ensuring better growth and yield. Mulching enhances the resilience of fodder crops to extreme weather conditions, contributing to sustainable feed production in dairy systems.

Integrated Pest Management

Integrated pest management (IPM) combines biological, cultural, mechanical, and chemical practices to control pests in a sustainable and eco-friendly manner [3, 23, 24, 31]. By using natural predators, crop rotation, and resistant varieties, IPM minimizes the reliance on chemical pesticides, promoting healthier fodder crops. This climate-smart approach improves fodder quality and yields while reducing the environmental impact of pest control, ensuring long-term feed security for dairy farms.

GENETIC INTERVENTIONS

Breeding for High-Yield Fodder Varieties

Breeding high-yield fodder varieties focuses on improving the productivity of fodder crops through selective breeding techniques [4, 24, 51, 62]. By enhancing traits such as growth rate, biomass, and nutritional content, farmers can produce more feed per unit area. High-yield varieties ensure a consistent and abundant supply of fodder for dairy cattle, supporting sustainable farming practices and increasing feed security in regions with limited resources.

Development of Pest-Resistant Fodder Species

Developing pest-resistant fodder species involves genetic modification or selective breeding to create plants with natural resistance to common pests [4, 24, 51, 62]. These species reduce the need for chemical pesticides, promoting environmental-friendly farming practices. Pest-resistant varieties improve fodder quality, minimize crop losses, and increase feed availability, thereby contributing to sustainable and cost-effective fodder production for dairy systems.

Genetically Modified Fodder Crops

Genetically modified (GM) fodder crops are engineered to have enhanced traits such as improved nutrient content, drought tolerance, or pest resistance [4, 24, 51, 62]. GM crops can increase fodder yield, reduce dependence on chemical inputs, and improve feed quality for dairy cattle. These innovations support sustainable dairy production by optimizing fodder availability, improving animal health, and ensuring higher productivity under challenging environmental conditions.

Use of Tissue Culture for Fodder Plants

Tissue culture is a biotechnological technique used to propagate fodder plants under controlled conditions. Tissue culture helps produce uniform and high-quality plants by cloning high-yielding or disease-resistant varieties, [4, 24, 51, 62]. This method allows rapid multiplication of desirable fodder species, improving feed availability and ensuring a consistent supply of nutritious feed. Tissue culture contributes to sustainable fodder production, especially in regions with limited land resources.

Development of Perennial Fodder Varieties

Development of perennial fodder varieties focus on breeding plants that produce feed for multiple years without the need to replant annually [4, 24, 51, 62]. Perennial species reduce the need for frequent sowing, labor, and inputs, offering a long-term solution for stable fodder supply. These varieties also improve soil health and minimize erosion, making them a sustainable option for dairy farming, particularly in areas with limited arable land.

COLLABORATIVE APPROACHES

Farmer Cooperatives for Fodder Banks

Farmer cooperatives for fodder banks enable farmers to collectively produce, store, and distribute fodder. By pooling resources, they can ensure a steady supply of quality feed during shortages [17, 45]. These cooperatives help reduce the financial burden on individual farmers, enhance fodder security, and support sustainable dairy farming by improving the accessibility of affordable and nutritious feed.

Public–Private Partnerships in Fodder Development

Public–private partnerships (PPPs) in fodder development bring together government agencies, private companies, and research institutions to address fodder-related challenges [17, 45]. These collaborations foster innovation in fodder production technologies, provide financial and technical support, and promote sustainable farming practices. PPPs create opportunities for farmers to access resources, expertise, and markets, ensuring long-term fodder availability and improving dairy production systems.

Knowledge Sharing among Farmers

Knowledge sharing among farmers facilitates the exchange of best practices, innovative techniques, and local experiences regarding fodder cultivation and management [17, 45]. Through farmer-to-farmer networks, workshops, and online platforms, farmers can learn about new technologies, climate-smart practices, and alternative feed resources. This collective learning enhances productivity, reduces risks, and fosters community-driven solutions to fodder challenges, supporting sustainable dairy farming.

Contract Farming for Fodder Production

Contract farming for fodder production involves formal agreements between farmers and buyers, such as dairy farms or fodder companies [17, 45]. These contracts guarantee a stable market for fodder and provide farmers with access to better inputs, technology, and training. By ensuring fair prices and reducing market risks, contract farming helps boost fodder production, supports sustainability, and strengthens supply chains in dairy farming systems.

Regional Fodder Exchange Programmes

Regional fodder exchange programmes enable farmers to trade or share fodder resources across regions facing different production challenges [17, 45]. These programmes help balance supply and demand for fodder, particularly during seasonal shortages. By facilitating the movement of fodder between regions, these programmes ensure continuous feed availability, reduce feed costs, and contribute to more resilient and sustainable dairy farming systems.

RESEARCH AND DEVELOPMENT

Research on Low-Cost Fodder Cultivation

Research on low-cost fodder cultivation focuses on identifying cost-effective methods for growing and producing fodder [23, 63–66]. This includes exploring alternative farming techniques, utilizing local resources, and selecting affordable inputs. By developing cost-efficient practices, research aims to make fodder production more accessible to smallholder farmers, reducing production costs and ensuring a sustainable and affordable feed supply for dairy farming.

Studies on Fodder Nutrient Quality

Studies on fodder nutrient quality aim to improve the nutritional value of fodder crops, enhancing their digestibility and overall benefit to livestock. Research explores the optimal nutrient composition, the effects of various fertilization techniques, and the potential for genetic improvement of fodder species [23, 63–66]. These studies contribute to better feed efficiency, improved animal health, and higher milk and meat production in dairy systems.

Development of Efficient Fodder Harvesting Tools

The development of efficient fodder harvesting tools focuses on designing machinery and techniques that reduce labor costs, improve harvesting efficiency, and minimize feed losses. Research in this area includes innovations in mowing, chopping, and transporting fodder, helping farmers maximize yield and quality [23, 63–66]. Efficient harvesting tools contribute to more sustainable and cost-effective fodder production, supporting better feed availability for dairy farming.

R&D for Enhancing Fodder Digestibility

Research and development (R&D) for enhancing fodder digestibility focuses on improving the nutritional value and breakdown of feed in livestock. By exploring new varieties, processing methods, and additives, R&D aims to increase the bioavailability of nutrients in fodder, improving animal health and production efficiency [23, 63–66]. This research leads to higher-quality feed and more efficient milk and meat production in dairy systems.

Monitoring Fodder Productivity Trends

Monitoring fodder productivity trends involves tracking yield variations and assessing the impact of different farming practices, climatic conditions, and resource management strategies on fodder output [23, 63–66]. This research helps identify the most productive and sustainable fodder varieties and practices, guiding farmers in optimizing feed production. Understanding productivity trends supports decision-making, improving the resilience and sustainability of dairy farming systems in the face of environmental changes.

EDUCATION AND EXTENSION

Farmer Field Schools for Fodder Production

Farmer field schools for fodder production provide an interactive learning platform where farmers can gain hands-on experience in fodder cultivation and management [14, 17, 39, 67, 68]. These schools offer practical demonstrations on improved farming techniques, pest control, and resource management. By engaging farmers in real-world applications, field schools empower them with the knowledge to increase fodder production and enhance dairy farming sustainability.

Demonstrations on Fodder Management

Demonstrations on fodder management offer farmers practical insights into efficient fodder production and handling [14, 17, 39, 67, 68]. These demonstrations cover aspects such as seed selection, soil preparation, irrigation, and pest management. By showcasing successful methods, these programmes help farmers adopt better practices, optimize yield, and ensure the year-round availability of quality feed, contributing to improved livestock health and productivity.

Extension of Fodder Technologies

Extension of fodder technologies involves disseminating advanced research and innovations related to fodder production to farmers through extension services [14, 17, 39, 67, 68]. This includes introducing new fodder varieties, efficient irrigation systems, and modern harvesting techniques. Extension programmes bridge the gap between research institutions and farmers, ensuring the widespread adoption of technologies that enhance fodder production and contribute to sustainable dairy farming systems.

Farmer-Led Fodder Innovation Systems

Farmer-led fodder innovation systems encourage farmers to take an active role in developing and testing new fodder cultivation practices, techniques, and technologies. By fostering innovation at the grassroots level, these systems leverage local knowledge and practical experience [14, 17, 39, 67, 68]. Farmer-led initiatives promote sustainable fodder solutions tailored to local conditions, improving the adaptability and resilience of fodder production systems and enhancing overall productivity.

Peer-to-Peer Knowledge Transfer

Peer-to-peer knowledge transfer enables farmers to share practical experiences, insights, and best practices regarding fodder cultivation and management. Through informal networks, farmer groups, and community meetings, farmers can learn from one another's successes and challenges [14, 17, 39, 67, 68]. This exchange of knowledge strengthens farming communities, accelerates the adoption of improved techniques, and fosters a collective approach to solving fodder-related issues in sustainable dairy farming systems.

ECONOMIC INTERVENTIONS

Microfinancing for Fodder Cultivation

Microfinancing for fodder cultivation provides small-scale farmers with affordable loans and financial services to support the establishment and expansion of fodder production [32, 35, 69–71]. This approach helps farmers invest in quality seeds, equipment, and infrastructure, ensuring consistent fodder supply. By improving access to capital, microfinancing empowers farmers to boost productivity, reduce dependency on external feed sources, and enhance the economic sustainability of dairy farming.

Formation of Fodder Credit Societies

Formation of fodder credit societies enables farmers to collectively access financial resources for fodder-related activities, such as purchasing seeds, fertilizers, and equipment. These societies pool funds from members, offering affordable loans to support fodder production. By fostering collective financial support, these societies promote increased fodder availability, reduce financial barriers, and improve the overall economic viability of fodder farming in rural communities [32, 35, 69–71].

Insurance Schemes for Fodder Crops

Insurance schemes for fodder crops provide financial protection against risks such as droughts, floods, and pest outbreaks that can negatively impact fodder production [32, 35, 69–71]. These schemes help safeguard farmers' investments by covering losses due to adverse weather conditions and natural disasters. With adequate insurance coverage, farmers can mitigate the financial risks associated with fodder cultivation, ensuring stability in feed availability for livestock.

Pricing Policies for Fodder Seeds

Pricing policies for fodder seeds focus on setting fair and affordable prices for high-quality fodder varieties, making them accessible to farmers [32, 35, 69–71]. Such policies can reduce the cost of inputs for fodder cultivation, encouraging farmers to invest in better seed quality and more sustainable practices. By regulating pricing, these policies contribute to the overall economic efficiency and sustainability of fodder production in dairy systems.

Market Development for Fodder Crops

Market development for fodder crops involves creating and expanding market opportunities for fodder producers, both locally and regionally. This includes improving supply chains, providing access to reliable buyers, and establishing fair pricing systems. By developing robust markets, farmers are incentivized to increase fodder production, ensuring a consistent and sustainable feed supply. Enhanced market access also encourages investment and innovation in fodder cultivation [32, 35, 69–71].

WASTE MINIMIZATION

Utilization of Crop Residues as Green Feed

Utilization of crop residues as green feed involves repurposing agricultural byproducts, such as straw and husks, as nutritious feed for livestock [29, 72, 73]. This practice reduces waste, improves feed security, and minimizes environmental pollution. By incorporating crop residues into livestock diets, farmers can decrease feed costs, promote sustainability, and enhance the efficiency of agricultural resource use, contributing to more sustainable farming systems.

Conversion of Vegetable Waste into Green Fodder

Conversion of vegetable waste into green fodder involves transforming plant waste from the vegetable sector, such as leaves, stems, and peels, into valuable feed for livestock [29, 72, 73]. This process not only reduces food waste but also creates a sustainable and cost-effective fodder source. By recycling vegetable waste, farmers can improve their feed supply, enhance animal nutrition, and minimize the environmental impact of agricultural waste.

Reduction of Post-Harvest Fodder Loss

Reduction of post-harvest fodder loss focuses on minimizing spoilage and wastage of fodder after harvest. This includes improving storage techniques, ensuring proper handling, and employing drying methods to preserve the nutritional quality of fodder. By reducing losses, farmers can maximize fodder availability, decrease feed shortages, and reduce dependency on external feed sources, contributing to the sustainability and economic viability of dairy farming systems [29, 72, 73].

Recycling of Agricultural Wastewater for Fodder

Recycling of agricultural wastewater for fodder involves using treated wastewater from irrigation or other agricultural processes to irrigate fodder crops [29, 72, 73]. This practice conserves fresh water, reduces waste, and supports sustainable fodder production. By repurposing wastewater, farmers can maintain a consistent supply of water for crop cultivation, improving the efficiency of water use and contributing to sustainable agricultural practices in water-scarce regions.

Composting Non-Edible Residues for Fertilization

Composting non-edible residues for fertilization involves converting agricultural waste, such as crop stems, leaves, and other non-consumable parts, into nutrient-rich compost for soil enrichment. This process reduces waste, improves soil fertility, and supports sustainable fodder production. By recycling organic residues into compost, farmers can reduce their reliance on synthetic fertilizers, enhance soil health, and improve the sustainability of their farming operations [29, 72, 73].

SUSTAINABILITY-FOCUSED PRACTICES

Emphasis on Organic Fodder Production

Emphasis on organic fodder production promotes the cultivation of fodder without synthetic pesticides, fertilizers, or genetically modified organisms [14, 23, 39, 46, 51, 74]. This approach enhances soil health, reduces chemical residue in animal products, and supports ecological balance. By focusing on organic methods, farmers can produce nutritious and environmentally friendly feed while contributing to the overall sustainability of the farming system and reducing the environmental footprint of livestock production.

Inclusion of Underutilized Fodder Species

Inclusion of underutilized fodder species involves integrating lesser-known, drought-tolerant, and nutritious plants into fodder systems [14, 23, 39, 46, 51, 74]. These species can thrive in challenging climates and poor soils, offering resilience to climate variability and reducing reliance on conventional fodder crops. By diversifying fodder sources, farmers enhance system stability, preserve biodiversity, and improve the nutritional variety available for livestock, contributing to sustainable dairy farming.

Promotion of Zero-Waste Fodder Systems

Promotion of zero-waste fodder systems focuses on maximizing the use of all available resources in fodder production, from reducing waste in cultivation to utilizing by-products for feed. This includes composting, recycling, and reusing agricultural residues to create a closed-loop system [14, 23, 39, 46, 51, 74]. By promoting zero-waste practices, farmers can enhance resource efficiency, minimize environmental impact, and ensure a continuous supply of high-quality fodder for livestock.

Sustainable Mechanization Practices

Sustainable mechanization practices involve adopting energy-efficient, low-emission machinery for fodder cultivation, harvesting, and processing [14, 23, 39, 46, 51, 74]. These technologies reduce fuel consumption, lower greenhouse gas emissions, and improve operational efficiency. By integrating sustainable mechanization, farmers can reduce their carbon footprint, enhance productivity, and minimize the environmental impact of fodder production, making farming more resource-efficient and climate-resilient.

Strengthening Biodiversity in Fodder Systems

Strengthening biodiversity in fodder systems involves integrating a variety of plant species, including legumes, grasses, and shrubs, into fodder production [14, 23, 39, 46, 51, 74]. This approach improves ecosystem resilience, enhances soil fertility, and supports natural pest control. By promoting biodiversity, farmers can reduce dependency on single-crop systems, protect the environment, and ensure a sustainable, diversified, and nutritious feed supply for livestock.

URBAN INTERVENTIONS

Rooftop Farming for Fodder Crops

Rooftop farming for fodder crops utilizes urban rooftops to cultivate fodder, especially in areas with limited agricultural land [12, 23]. This innovative approach maximizes underutilized spaces, reduces the urban heat island effect, and provides a sustainable source of fresh feed for livestock. Rooftop fodder farming contributes to local food security, reduces transportation costs, and enhances the resilience of urban agriculture.

Utilization of Urban Vacant Spaces for Fodder

Utilization of urban vacant spaces for fodder involves converting unused land within cities, such as vacant lots or abandoned buildings, into productive areas for fodder cultivation. This practice helps reduce urban waste, promotes local food production, and alleviates pressure on rural lands. By repurposing urban spaces for fodder, cities can enhance food security, reduce transportation costs, and make urban agriculture more sustainable [12, 23].

Collaboration with Peri-Urban Farmers

Collaboration with peri-urban farmers fosters partnerships between urban and rural areas to improve fodder supply chains [12, 23]. By connecting urban markets with nearby rural farms, this approach creates more efficient distribution channels, reduces transportation costs, and improves feed availability. Strengthening these relationships helps ensure a stable and affordable supply of fodder for urban livestock, contributing to food security and economic sustainability.

Urban Fodder Production Models

Urban fodder production models focus on developing systems within cities to grow and distribute fodder efficiently [12, 23]. These models may include vertical farming, rooftop gardens, and hydroponics to produce fodder crops in limited spaces. By implementing such models, urban areas can ensure a consistent and sustainable feed supply, reducing reliance on rural areas and promoting local food systems that are resilient and environmentally friendly.

City-Based Fodder Supply Chains

City-based fodder supply chains aim to create efficient networks for sourcing, processing, and distributing fodder within urban areas [12, 23]. This approach minimizes transportation costs, ensures fresh supply, and reduces reliance on rural areas. By developing local supply chains, cities can enhance food security, reduce carbon footprints, and support urban farmers in maintaining a steady supply of fodder for livestock, promoting sustainability in urban agriculture.

CONCLUSION

Optimizing green fodder availability is pivotal for enhancing the sustainability of dairy farming in the tropics. This study underscores the importance of adopting high-yielding, climate-resilient fodder varieties, innovative cultivation methods, and resource-efficient technologies to address challenges such as seasonal fluctuations and limited land availability. Integrating traditional practices with modern solutions, including hydroponics, agroforestry, and precision agriculture, offers a viable pathway to ensure year-round fodder supply. Emphasizing community-based models and policy support can further enhance accessibility and adoption among smallholder farmers. By providing a comprehensive roadmap, this study contributes to improving dairy productivity, reducing environmental impact, and ensuring economic viability. Implementing these strategies can foster sustainable dairy development while addressing the growing demand for dairy products in tropical regions.

Future Directions

Future research should focus on developing and promoting climate-resilient fodder species that can thrive under the diverse environmental conditions of the tropics. Advancements in genetic engineering and molecular breeding could enhance fodder quality, drought tolerance, and biomass yield. Exploring the integration of digital technologies, such as remote sensing and artificial intelligence, may optimize resource allocation and monitor fodder growth in real-time. Scaling up innovative practices like hydroponic and vertical farming requires assessing their economic feasibility and adaptability for smallholder farmers. Investigating the socio-economic impacts of community-based models, such as fodder banks and cooperative farming, could provide insights into enhancing adoption. Additionally, formulating supportive policies and extension programs to disseminate knowledge and technology is critical. Addressing these aspects holistically can drive sustainable improvements in fodder availability and contribute to resilient and economically viable dairy farming systems in the tropics.

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